Spectropolarimetry of epsilon Aurigae: Probing Stellar and Disk Atmospheres

Kathleen Marie Geise

University of Denver

Follow this and additional works at: https://digitalcommons.du.edu/etd

Recommended Citation

https://digitalcommons.du.edu/etd/235

This Dissertation is brought to you for free and open access by the Graduate Studies at Digital Commons @ DU. It has been accepted for inclusion in Electronic Theses and Dissertations by an authorized administrator of Digital Commons @ DU. For more information, please contact jennifer.cox@du.edu.
Spectropolarimetry of epsilon Aurigae: Probing Stellar and Disk Atmospheres

A Dissertation
Presented to
the Faculty of Natural Sciences and Mathematics
University of Denver

in Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy

by
Kathleen M. Geise
June 2015
Advisor: Dr. Robert Stencel
Abstract

The bright eclipsing binary system ε Aurigae offers a unique opportunity to uncover physical mechanisms contributing to disk formation and evolution and to explore the relationship between photospheric anisotropies, stellar pulsation and mass loss. This research contributes to our understanding of stellar evolution in the context of binary stars. The research also offers the opportunity to investigate disk formation and evolution significant to our understanding of protoplanetary disks now seen in many star systems. Lastly, the project considers radiative transfer of polarized light which contributes to diverse fields such as atmospheric studies of exoplanets.

My objective is to understand the evolutionary status of the eclipsing disk in the ε Aurigae system by exploring the distribution of gas and characteristics of dust grains in the disk. I evaluated spectral features and linear polarization in ESPaDOnS out-of-eclipse spectra in order to characterize line polarization observed in the system. It is important to understand the out-of-eclipse behavior in order to correctly differentiate signals seen in ESPaDOnS spectra taken during the most recent (2009–2011) eclipse. This thesis work tested the hypothesis that the F0 star in the system shows intrinsic broadband polarization and that the percent linear polarization (%p) is related to the brightness of the variable F0 star observed out-of-eclipse. Uncovering the position angle of intrinsic linear polarization also tested whether dust grains in the disk are small (<1µm) or large (>10µm).
I evaluated spectral features and line polarization of select disk lines before, during and after eclipse in order to better resolve the distribution of gas in the disk. Significant ($\geq 4\sigma$) linear polarization peaks are associated with spectral absorption features and the scattering geometry is revealed by an analysis of the dominant polarization position angles. I characterized the contribution of interstellar polarization using archived data from the HPOL polarimeter and from published broadband filter data and subtracted the interstellar component from broadband out-of-eclipse and in-eclipse observations to characterize the intrinsic continuum polarization of the system. Results of these efforts are itemized below.

First, linear polarization is persistent in out-of-eclipse observations, appears strongest in the core of each associated spectral line and is variable in time and strength. The polarization observed out-of-eclipse likely arises from an equatorial density enhancement in the gas in the outer layers of the F0 star.

Second, disk rotation signatures appear in eclipse polarization spectra in both low energy ($E_{\text{II}} < 3$ eV) and high energy ($E_{\text{II}} > 3$ eV) atomic transitions just after mid-eclipse even when additional absorption does not appear to be present in the line. Linear polarization (%$p$) is bi-lobed and Stokes $U$ is antisymmetric through the line at these times. These polarimetric signatures are consistent with line polarization in models of optically thick rotating disks.

Third, an increase in line polarization precedes an increase in continuum polarization near eclipse 3rd contact. This is due to a density enhancement in the disk located on the side of the disk illuminated by the F0 star but offset from the direct line in the direction of disk rotation. I propose that scattering angles imposed by the system geometry are responsible for the phenomenon. Line polarization is stronger
at egress than ingress supporting a model in which a temperature gradient is present in the disk, and the back side of the disk extends above the dusty opaque layer after mid–eclipse.

Finally, intrinsic continuum polarization observed out-of-eclipse (OOE) is sometimes wavelength–dependent. Changes to \( \% p \) are not correlated with changes in F0 star brightness. I uncovered the underlying intrinsic polarization in published eclipse data to find an intrinsic linear polarization position angle of \( \sim 90^\circ \) in the stellar/disk reference frame during mid–eclipse phases. Polarization during eclipse primarily arises from forward–scattering at large dust grains or from multiple scattering from optically–thick dusty material. Optically thin scattering from small grains would yield position angles closer to \( 0^\circ \) in the stellar/disk reference frame. The presence of large dust grains suggests that the disk is an evolved debris disk rather than a young proto-planetary disk and that the F0 star in the system is an evolved star.
Acknowledgements

I would like to thank the University of Denver and my advisor, Robert Sten-cel. I would also like to offer very special thanks to Herschel Neumann, professor emeritus and former Chairman of the University of Denver, Department of Physics and Astronomy. I would like to thank the members of the committee that reviewed this manuscript at the University of Denver: Paul Hemenway, Jennifer Hoffman and Mark Siemens. Thank you to Roberto Casini, Elizabeth Griffin, Philip Judge, Brian Kloppenborg, John Landstreet, Bruce Lites, Richard Pearson and Jan Stenflo for many helpful discussions and to August Geise for German language translation. Many thanks to the faculty, staff and students at the DU Department of Physics and Astronomy for mentorship and collaboration, and to the observers and staff of the American Association of Variable Star Observers for providing nearly continuous eclipse photometry of the ε Aurigae system. Finally, thank you to my family for their encouragement and support.
Contents

1 Introduction .................................................. 1
  1.1 Why ε Aurigae? ............................................. 1
  1.2 Scope of this dissertation ................................. 1
  1.3 The ε Aurigae system ....................................... 3
    1.3.1 Mass scenarios and evolutionary status ............... 4
  1.4 Polarization of starlight .................................. 7
  1.5 Spectropolarimetry ........................................ 12
  1.6 Archive search for analog systems ....................... 13
    1.6.1 Catalogs searched .................................... 14
    1.6.2 Hα emission .......................................... 15
    1.6.3 Linear polarization ................................... 18
    1.6.4 Results of archive search ............................ 18
  1.7 Outline of dissertation .................................. 18
    1.7.1 Thesis ................................................ 18
    1.7.2 Method ................................................. 19
    1.7.3 Results ................................................. 19

2 Eclipse Spectropolarimetry of the ε Aurigae System .......... 34
  2.1 Summary ................................................... 34
  2.2 Introduction .............................................. 34
  2.3 Observations .............................................. 35
    2.3.1 Contributions of polarimetry to the study of ε Aur 35
  2.4 Method ..................................................... 37
  2.5 Analysis ................................................... 41
    2.5.1 Linear polarization time series and QU-plots ....... 41
    2.5.2 Hydrogen alpha ....................................... 41
    2.5.3 Hydrogen alpha polarization position angle ......... 44
    2.5.4 Hydrogen beta ........................................ 44
    2.5.5 Hydrogen gamma and Hydrogen delta .................. 46
    2.5.6 Potassium (769.896 nm) ................................ 46
    2.5.7 Calcium (422.673 nm) ................................ 48
    2.5.8 Circular polarization and Stokes V .................... 51
  2.6 Results .................................................... 52
  2.7 Conclusions and next steps ................................ 54
  2.8 Afterword ................................................ 54
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Probing disk inhomogeneities using spectropolarimetry in the extreme binary epsilon Aurigae</td>
<td>67</td>
</tr>
<tr>
<td>3.1</td>
<td>Summary</td>
<td>67</td>
</tr>
<tr>
<td>3.2</td>
<td>Introduction</td>
<td>67</td>
</tr>
<tr>
<td>3.3</td>
<td>Observations &amp; Methods</td>
<td>68</td>
</tr>
<tr>
<td>3.4</td>
<td>Results &amp; Conclusions</td>
<td>69</td>
</tr>
<tr>
<td>3.5</td>
<td>Afterword</td>
<td>71</td>
</tr>
<tr>
<td>4</td>
<td>An analysis of the most polarized atomic lines in ESPaDOnS out-of-eclipse observations of epsilon Aurigae</td>
<td>85</td>
</tr>
<tr>
<td>4.1</td>
<td>Summary</td>
<td>85</td>
</tr>
<tr>
<td>4.2</td>
<td>Introduction</td>
<td>86</td>
</tr>
<tr>
<td>4.2.1</td>
<td>F0 star</td>
<td>86</td>
</tr>
<tr>
<td>4.3</td>
<td>Observations and reductions</td>
<td>90</td>
</tr>
<tr>
<td>4.3.1</td>
<td>Spectra and spectropolarimetry</td>
<td>90</td>
</tr>
<tr>
<td>4.3.2</td>
<td>Stellar reference frame</td>
<td>92</td>
</tr>
<tr>
<td>4.3.3</td>
<td>Equivalent width</td>
<td>92</td>
</tr>
<tr>
<td>4.3.4</td>
<td>Line strength</td>
<td>93</td>
</tr>
<tr>
<td>4.3.5</td>
<td>Linear polarization</td>
<td>94</td>
</tr>
<tr>
<td>4.3.6</td>
<td>Line selection</td>
<td>95</td>
</tr>
<tr>
<td>4.4</td>
<td>Results and analysis: total flux spectra</td>
<td>97</td>
</tr>
<tr>
<td>4.4.1</td>
<td>K I (766.490 nm, 769.896 nm)</td>
<td>97</td>
</tr>
<tr>
<td>4.5</td>
<td>Results and analysis: spectropolarimetry</td>
<td>99</td>
</tr>
<tr>
<td>4.5.1</td>
<td>Hydrogen</td>
<td>100</td>
</tr>
<tr>
<td>4.5.2</td>
<td>Polarization in a remarkable out-of-eclipse Hα profile variation</td>
<td>100</td>
</tr>
<tr>
<td>4.6</td>
<td>Discussion and conclusions</td>
<td>102</td>
</tr>
<tr>
<td>4.7</td>
<td>Afterword</td>
<td>104</td>
</tr>
<tr>
<td>5</td>
<td>ESPaDOnS Spectropolarimetry of the epsilon Aurigae system: the gaseous disk in scattered light</td>
<td>129</td>
</tr>
<tr>
<td>5.1</td>
<td>Summary</td>
<td>129</td>
</tr>
<tr>
<td>5.2</td>
<td>Introduction</td>
<td>130</td>
</tr>
<tr>
<td>5.2.1</td>
<td>Spectra</td>
<td>131</td>
</tr>
<tr>
<td>5.2.2</td>
<td>Disk atmosphere</td>
<td>132</td>
</tr>
<tr>
<td>5.2.3</td>
<td>Disk models</td>
<td>134</td>
</tr>
<tr>
<td>5.2.4</td>
<td>Polarization</td>
<td>135</td>
</tr>
<tr>
<td>5.3</td>
<td>Observations and reductions</td>
<td>137</td>
</tr>
<tr>
<td>5.3.1</td>
<td>Spectra and spectropolarimetry</td>
<td>137</td>
</tr>
<tr>
<td>5.3.2</td>
<td>Magnitudes</td>
<td>138</td>
</tr>
<tr>
<td>5.3.3</td>
<td>Disk/stellar reference frame</td>
<td>138</td>
</tr>
<tr>
<td>5.3.4</td>
<td>Linear polarization</td>
<td>139</td>
</tr>
<tr>
<td>5.3.5</td>
<td>Line selection</td>
<td>140</td>
</tr>
<tr>
<td>5.3.6</td>
<td>Gas rotation</td>
<td>141</td>
</tr>
<tr>
<td>5.4</td>
<td>Results and analysis: total flux spectra</td>
<td>143</td>
</tr>
</tbody>
</table>
5.4.1 Fe II (658.671 nm, 656.220 nm) ........................................ 143
5.4.2 Disk spectral signatures ................................................. 144
5.5 Results and analysis: spectropolarimetry ............................... 145
  5.5.1 1st contact to 2nd contact ......................................... 145
  5.5.2 Mid–eclipse to 3rd contact ......................................... 147
  5.5.3 Late eclipse ............................................................ 148
  5.5.4 Spectral lines without disk absorption during eclipse .......... 149
  5.5.5 Spectral lines with disk absorption during eclipse ............. 151
  5.5.6 High eccentricity lines ............................................ 152
5.6 Discussion ................................................................. 155
  5.6.1 Scattered light at mid–eclipse .................................... 155
  5.6.2 Comparison to continuum polarization ........................... 158
  5.6.3 Disk rotation .......................................................... 159
5.7 Conclusions and next steps .............................................. 160
5.8 Afterword .................................................................... 162
6 HPOL out–of–eclipse observations of ε Aurigae .......................... 210
  6.1 Summary .................................................................... 210
  6.2 Introduction ............................................................... 211
  6.3 Observations and Reductions ............................................ 214
    6.3.1 Spectra ............................................................... 215
    6.3.2 Broadband filter data ............................................. 216
    6.3.3 Polarized flux ....................................................... 217
    6.3.4 Uncertainties ....................................................... 217
    6.3.5 Balmer jump ......................................................... 218
    6.3.6 Interstellar polarization ....................................... 219
    6.3.7 Adopted model for interstellar polarization .................. 220
  6.4 Results and analysis: Out–of–eclipse ................................ 221
    6.4.1 General polarization features .................................. 221
    6.4.2 Intrinsic polarization – spectra ................................ 222
    6.4.3 Intrinsic polarization – broadband filters .................... 223
    6.4.4 Intrinsic polarization – Balmer jump .......................... 223
  6.5 Results and analysis: Eclipse .......................................... 225
    6.5.1 General polarization features .................................. 225
    6.5.2 Intrinsic polarization – broadband filters .................... 225
  6.6 Discussion ................................................................. 227
    6.6.1 Out–of–eclipse ..................................................... 227
    6.6.2 Balmer index polarization ...................................... 228
    6.6.3 Eclipse ............................................................... 229
  6.7 Conclusions .................................................................. 230
  6.8 Afterword .................................................................... 232
  6.9 Supplement ............................................................... 233
    6.9.1 Interstellar polarization ......................................... 233
# Conclusions

## 7.1 Summary

## 7.2 The Epsilon Aurigae system in light of the spectropolarimetric observations

## 7.3 F0 star considerations

### 7.3.1 Evolutionary status and mass loss

### 7.3.2 Hα emission

## 7.4 Future work

## Bibliography

## Appendix
List of Tables

1.1 F Star Archive Spectra ............................................. 22
2.1 Log of ESPaDOnS Observations ................................. 56
4.1 Log of Observations (out–of–eclipse) ......................... 105
4.2 Equivalent widths .................................................. 106
4.3 Polarized flux equivalent width ................................. 109
4.4 Line core average linear polarization (%p) ..................... 111
4.5 Line core average position angle ............................... 114
4.6 Atomic transitions ................................................. 116
5.1 Log of Observations (epoch–binned) ......................... 163
5.2 Equivalent width: Pre–eclipse to 2nd contact ................. 165
5.3 Equivalent width: Mid–eclipse and beyond .................... 169
5.4 Polarized flux EW: Pre–eclipse to 2nd contact ............... 173
5.5 Polarized flux EW: Mid–eclipse to post–eclipse ............... 177
5.6 Atomic transitions ................................................. 181
6.1 Adopted orbital parameters ....................................... 240
6.2 HPOL observations of ε Aurigae ............................... 241
6.3 HPOL Synthetic UBVRI Filter Data for eps Aur ............. 242
6.4 FCO observations of ε Aurigaeα ................................ 244
6.5 Epsilon Aurigae Average Magnitudes ......................... 245
6.6 Serkowski law fit to HPOL spectra ............................ 246
6.7 Linear fits to broadband filter data ............................ 247
6.8 HPOL systematic broadband filter uncertainties ............. 248
6.9 HPOL Synthetic Balmer Jump Filter Data .................... 249
6.10 Intrinsic polarization ............................................. 250
6.11 Polarization of stars in the vicinity of ε Aurigaeα .......... 252
A.1 Master line list .................................................... 301
List of Figures

1.1 Artist rendering of the ε Aurigae system ................................................. 24
1.2 Top–down view of orbit. ................................................................. 25
1.3 Mass loss across the HR diagram ......................................................... 26
1.4 Hα line profile of ε Aurigae. ............................................................... 27
1.5 α Lep and α Per Hα line profiles ......................................................... 28
1.6 b Vel variable Hα line profiles ............................................................ 29
1.7 LN Hya Hα line profile. ................................................................. 30
1.8 V814 Her Hα line profiles. ............................................................... 31
1.9 89 Her Hα linear polarization. ............................................................ 32
1.10 V382 Aur Hα linear polarization ......................................................... 33

2.1 Time series of H–alpha (656.280 nm) .................................................. 58
2.2 QU–plots of H–alpha (656.280 nm) ....................................................... 59
2.3 Position angle calculated for the H–alpha line ....................................... 60
2.4 Time series of H–beta (486.135 nm) .................................................... 61
2.5 QU–plots of H–beta (486.135 nm) ....................................................... 62
2.6 Time series of K i (769.896 nm) .......................................................... 63
2.7 QU–plots of K i (769.896 nm) ............................................................ 64
2.8 Time series of Ca i (422.673 nm) .......................................................... 65
2.9 QU–plots of Ca i (422.673 nm) ............................................................ 66

3.1 Composite image of ε Aurigae .............................................................. 72
3.2 Fe ii (4657 Å) line profiles. ............................................................... 73
3.3 Fe ii (4657 Å) QU–plot ................................................................. 74
3.4 Fe ii (4657 Å) equivalent width (EW) ................................................. 75
3.5 Fe ii (4657 Å) polarized flux EW ......................................................... 76
3.6 Fe ii (4924 Å) line profiles ............................................................... 77
3.7 Fe ii (4924 Å) QU–plot ................................................................. 78
3.8 Fe ii (4924 Å) equivalent width .......................................................... 79
3.9 Fe ii (4924 Å) polarized flux EW ......................................................... 80
3.10 K i (7699 Å) equivalent width .......................................................... 81
3.11 K i (7699 Å) polarized flux EW ......................................................... 82
3.12 H i (6563 Å, Hα) EW ................................................................. 83
3.13 H i (6563 Å, Hα) pol flux EW ........................................................... 84

4.1 Fe II (501.844 nm) and Mg II (517.268 nm) line variability .................. 118
4.2 Fe II (450.827 nm) line corrected for stellar motion ............................. 119
4.3 K I (769.896 nm) line and residual normalized intensity. .................... 120
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.8</td>
<td>HPOL spectra intrinsic polarization</td>
<td>260</td>
</tr>
<tr>
<td>6.9</td>
<td>HPOL spectra intrinsic position angle</td>
<td>261</td>
</tr>
<tr>
<td>6.10</td>
<td>Comparison of intrinsic polarization in HPOL data (1990–12–02)</td>
<td>262</td>
</tr>
<tr>
<td>6.11</td>
<td>Intrinsic polarization in broadband data</td>
<td>263</td>
</tr>
<tr>
<td>6.12</td>
<td>Intrinsic polarization PA in broadband data</td>
<td>264</td>
</tr>
<tr>
<td>6.13</td>
<td>Intrinsic V band linear polarization by phase</td>
<td>265</td>
</tr>
<tr>
<td>6.14</td>
<td>Intrinsic V band linear polarization PA by phase</td>
<td>266</td>
</tr>
<tr>
<td>6.15</td>
<td>Intrinsic B band linear polarization by phase</td>
<td>267</td>
</tr>
<tr>
<td>6.16</td>
<td>Intrinsic B band linear polarization PA by phase</td>
<td>268</td>
</tr>
<tr>
<td>6.17</td>
<td>Rotated Balmer jump index data</td>
<td>269</td>
</tr>
<tr>
<td>6.18</td>
<td>QU–plot of broadband filter data from mid–eclipse to 4th contact</td>
<td>270</td>
</tr>
<tr>
<td>6.19</td>
<td>HPOL V band ISP Case B</td>
<td>271</td>
</tr>
<tr>
<td>7.1</td>
<td>Blueness of scattered light during eclipse</td>
<td>282</td>
</tr>
<tr>
<td>7.2</td>
<td>Model of polarization near 3rd contact</td>
<td>283</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

1.1 Why $\epsilon$ Aurigae?

Observers of the system have called $\epsilon$ Aurigae mysterious, puzzling, unique and enigmatic. At least one observer has been moved to recite poetry (from Robert Frost): “We dance round in a ring and suppose, but the Secret sits in the middle and knows” (Wilson, 1971). One aspect of the system does set it apart from almost all other binary systems viewed from Earth: the eclipse is seen nearly edge-on. Because of this geometry, the luminous primary star acts as probing beam of light illuminating portions of the disk as it passes in front of the star. This remarkable coincidence of nature offers an unparalleled opportunity to explore the physics of disk formation and evolution in what appears to be an actively interacting system. In addition, the irregularly pulsating F0 star in the system tests our knowledge of stellar structure and evolution because the star appears to exist tenuously at the edge of hydrostatic equilibrium.

1.2 Scope of this dissertation

I present the results of a study of asymmetries in the $\epsilon$ Aurigae system. The asymmetries arise because of the binary nature of the system, the eclipse and other changes to the geometry of the system with orbit, and importantly and somewhat unexpectedly, asymmetries in the photosphere of the F0 star, the dominant source of visible light in the system. The persistent asymmetries in the F0 star atmosphere, coupled with large atmospheric macroturbulence (e.g. Hack, 1959), point to
energy propagation in the outer atmosphere of the primary star that support my premise that mass loss is occurring or has occurred with this star. This mass loss may contribute to the long-term stability of the disk observed in the system by replacing mass accreted from the disk onto the companion. The disk appears to be stable, at least on the time-scale of the past 80–100 years (Griffin and Stencel, 2013).

Linear polarization associated with gas in the outer atmosphere of the F0 star (discussed in Chapter 4) strongly suggests that at least some of the observed continuum polarization arises from persistent, but variable, anisotropies in the F0 star atmosphere (Chapter 6). Are atmospheric anisotropies prevalent in evolved stars? If so, spectropolarimetric observations may may help uncover the physics of energy propagation in extended stellar atmospheres to promote our understanding of the later stages of stellar evolution and associated mass loss phenomena. All stars appear to lose mass as they age; the challenge is to uncover the underlying physical processes that contribute to mass loss and to asymmetries in the distribution of material sometimes observed surrounding evolved stars. Spectropolarimetry may be a useful tool in these studies.

Asymmetries in the distribution of gas in the disk are common to many gas species (Chapter 5). Nearly every polarized line observed in the ε Aurigae spectrum points to a large increase in scattering around the same time in the eclipse. A time–resolved phenomenon is also a spatially–resolved phenomenon because the eclipse was imaged interferometrically and also because the eclipse is seen edge–on. The spectropolarimetric signal near 3rd contact likely arises from an increase in the number of scatterers (gas atoms in this case) contributing to the polarization. The phenomenon is consistent across observed gas species and points to a suspected thermal effect from F0 star heating of the disk. The polarization arises from rotating gas
consistent with gas gravitationally-bound to the disk. This work highlights polarization from a well-studied disk that may inform observations of other astronomical disks.

Finally, medium resolution spectropolarimetry describes variability observed in continuum polarization over a range of orbital phases not covered by any other recent polarimetric observations (Chapter 6). These observations illustrate that the F0 star atmospheric asymmetries may exist well beyond eclipse phases. In addition, this analysis provides a roadmap for analyzing and removing the interstellar polarization contribution from broadband observations of \( \epsilon \) Aurigae in order to uncover any intrinsic component of the polarization present in the measurements.

1.3 The \( \epsilon \) Aurigae system

Epsilon Aurigae (HD 31964, HR 1605) is a bright \( (V \sim +3^{m}0) \), single-line spectroscopic binary system consisting of a spectral type F0Ia star and a binary companion embedded in an opaque dusty disk (see Fig. 1.1 for system model). The nature of the second star (or stars!) is debated, but an ultra-violet (UV) excess in the spectral energy distribution (SED) of the system suggests the second object is a spectral type B5 star (Hoard et al., 2010, hereafter HHS). The system eclipses once every 27 years for a duration of two years, the longest period of totality of known eclipsing systems. Epsilon Aurigae recently received unprecedented attention; the 2009–2011 eclipse offered professional and amateur astronomers an opportunity to observe a celestial rarity.

Many parameters, including the masses and evolutionary status of the components of the system, are not well-known because the distance is not well-determined. The system is far enough away that parallax measurements cannot be used to deter-
mine distance. Many observers have looked for evidence of the binary companion in spectra in order to define its motion and resolve the distance. Stencel et al. (2011) discovered transient He i (λ 10830Å) absorption near mid-eclipse and for several months afterward using the moderate resolution (R ∼ 2500), near-IR (1–5 µm) spectrometer SpeX located at the NASA Infrared Telescope Facility (IRTF). The signal was consistent with B star origin; however, the velocity resolution of the instrument was not sufficient to resolve the motion during the observation timeframes.

1.3.1 Mass scenarios and evolutionary status

Two models of the system are favored by observers of ε Aurigae: the (1) high mass and (2) low mass models (e.g. Guinan and Dewarf, 2002; Chadima et al., 2011, and references within). The models depend upon an assumed distance to the system or other system constraints (Fig. 1.2). In the high mass scenario, the F0 star is a high luminosity supergiant star of mass ∼15 M⊙ and the separation of the binary components is ∼30 AU. In the low mass scenario, the F0 star is an evolved Asymptotic Giant Branch (AGB) object, called a post–AGB star. One example of this type of solution was proposed by Eggleton and Pringle (1985). These authors proposed a post-AGB F0 star mass of 1.3 M⊙ and a companion of mass 5 M⊙, with the possibility that the hidden companion is actually a binary, make the total system a triple star system. Eggleton and Pringle applied mass function described by Morris (1962). A revised value for the parallax derived from Hipparcos satellite data yields a distance of ∼650 pc, but the uncertainty in the measurement is “astronomically” high (1.53 ± 1.29 mas) (van Leeuwen, 2007).

The variable F0 star in the system is observed in V band at about +3.0 magnitude, but the uncertain distance gives a range of possible values for the absolute magnitude and luminosity of the star. Stellar evolutionary tracks place a high mass
primary star ($M_1 = 20 \, M_\odot$ to $50 \, M_\odot$, distance $1500 \pm 500$ pc) at absolute visual magnitude $M_V = -7.9$ to $-10.2$ and luminosity of $\log L = 5.0 \, L_\odot$ to $6.0 \, L_\odot$ (Guinan et al., 2012). Typical supergiant stars have absolute visual magnitudes $M_V > -8$ mag (Castelli, 1978). In the stellar evolutionary model proposed by Guinan et al., the high mass F0 star has evolved away from the main sequence by now and has progressed to nuclear fusion of helium in the stellar core. The star becomes cooler and expands as it leaves the main sequence, but it has not lost more than 1% of its initial mass. In this scenario, the disk is either a long–lived proto–stellar or proto–planetary disk, or it may have been accreted by the secondary star when the primary lost mass through a super–wind during a Luminous Blue Variable (LBV) phase.

Stellar evolutionary tracks place a low mass F0 star at the same effective temperature but much lower luminosity than the high mass supergiant models (Guinan et al., 2012). The star begins with mass $7M_\odot$ and evolves off the main sequence and through the AGB until it reaches $\log L = 4.4 \, L_\odot$ ($M_{\text{bol}} = -6.2$ mag). In this scenario, the secondary star accretes material lost by the primary through mass loss typical of the AGB (Ueta et al., 2010). Many AGB and post–AGB objects are surrounded by dusty circumstellar material (Geise et al., 2010; Geise, 2011). Circumstellar dust is not observed around the F0 star in the $\varepsilon$ Aurigae system (Hoard et al., 2012), (c.f. Decin, 2012).

Potravnov (2012) placed the axial rotational velocity of the F0 star at $V \sin i = 38 \pm 0.5$ km s$^{-1}$. This velocity represents the true rotational velocity of the star because $i \approx 89^\circ$. Stellar evolutionary models that include rotation suggest a massive ($15M_\odot$) F0 star should have a rotational velocity of $\sim 10$ km s$^{-1}$ (Ekström et al., 2011). In these models, an F0 star with a rotational velocity of $\sim 40$ km s$^{-1}$
would have evolved from a $5M_\odot$ star (Ekström et al., 2011, Fig. 9). However, the authors note that the rotational velocity of a $9M_\odot$ stellar model briefly reached critical velocity and the star passed through a period of enhanced equatorial mechanical mass loss ($10^{-3}M_\odot$) during the Cepheid blue loop. In these models, the rotational velocity of a $9M_\odot$ model star changes by tens of km s$^{-1}$ in the Cepheid loop and could easily reach a state of F0 and $V \sin i \approx 30$ km s$^{-1}$ (Ekström et al., 2011, Fig. 9).

One further consideration with respect to stellar evolutionary models of the $\epsilon$ Aurigae system is binarity. Batten (1995) suggests that single star evolutionary models are appropriate for binary systems such as $\zeta$ Aurigae systems with long periods and large distances between objects, but that interaction between the components may take place in the supergiant phase (Batten, 1995, page 913). In interacting binary systems such as long–period (detached) Algol systems, binary interaction may result in the presence of a stable circumstellar disk around the secondary and may also affect the evolutionary paths of the stellar components in the system (Batten, 1995, page 903). In these cases, binary interaction, mass loss and mass transfer may be important components of any stellar evolutionary model of the system.

Stellar evolutionary models provide insight into the possible evolutionary state of the components of the $\epsilon$ Aurigae system and the mass loss processes that may have contributed to the formation of an accretion disk in the system. Single star evolutionary tracks allow for a more massive ($\approx 20 \ M_\odot$) hotter (type O) star to evolve to a luminous ($L \approx 5 \ L_\odot$) spectral type F star with mass loss possible during a LBV phase. A star of $9 \ M_\odot$ may evolve to a less luminous spectral type F star and lose mass by reaching critical rotational velocity while passing through the Cepheid blue loop. Finally, a low mass star ($1-7 \ M_\odot$) may evolve through the AGB stage to
a lower luminosity \( (L \approx 4.4 \, L_\odot) \) spectral type F star and lose mass through typical AGB mass loss processes. A robust solution for the distance to the system would establish the luminosity of the primary star and resolve the degeneracy in these possible stellar evolutionary models for the \( \varepsilon \) Aurigae system. Figure 1.3 provides a plot of effective temperature, absolute visual magnitude and mass loss rates from de Jager et al. (1988).

1.4 Polarization of starlight

Starlight becomes polarized when it interacts with matter, such as neutral and ionized gas species, astronomical dust, or free electrons. Local thermodynamic equilibrium (LTE) describes the region of a stellar atmosphere where the number of atoms in different ionization states is determined by the local temperature and where collisions occur frequently. Polarization requires non–LTE conditions so that the polarization state of outgoing photons is preserved as the photons traverse the medium. Polarization from light scattering at gas may occur at neutral atoms, ionized atoms or at molecules where the population of atomic levels and molecular species is driven by local conditions (temperature and pressure) and where collisions are not dominant (non–LTE). Polarization from electron scattering may occur in plasmas in non–LTE conditions. Polarization resulting from dust scattering may occur in environments cool enough so that dust can condense (< 1600 K).

Spherically symmetric scattering regions produce no net polarization. Scattered light produces non–zero linear polarization when the distribution of material is asymmetric, or the radiation is asymmetric. Polarization observed in starlight may be used to deduce the nature of the scattering agent, the geometry of the scattering region and if magnetic fields are present, the orientation and strength of the magnetic field. For example, when the scattering material is optically thin (gas, dust
or electrons) and the distribution is asymmetric, the resulting linear polarization is described by a pseudo–vector oriented perpendicular (90°) to the longest axis of the distribution.

Scattering of starlight at electrons, called **Thomson scattering**, is described as ‘gray’ because the resulting linear polarization has no wavelength dependence. However, subsequent wavelength–dependent absorption may impose a wavelength–dependence on the light polarized from scattering at electrons (e.g. Halonen et al., 2013). Electron scattering is isotropic with no preferred scattering angle.

Dust scattering from small grains ($a < 1 \mu$m) is described by Mie scattering theory and produces linear polarization that is wavelength–dependent. Astronomical dust (submicron grain size) is a common polarizer of starlight. In this case, the polarization is caused by selective directional scattering of light by the non–spherical dust particles which are aligned through interaction with the galactic magnetic field (Hall, 1958). For example, linear polarization from dust in the Interstellar Medium (ISM) of the Milky Way galaxy produces linear polarization that follows an empirical law known as the Serkowski Law (Serkowski et al., 1975). The light experiences differential extinction as it passes through regions of magnetically aligned, non-spherical interstellar dust grains. The wavelength dependence in the optical and near infrared is described by

$$\frac{p(\lambda)}{p_{\text{max}}} = \exp \left[ -K \ln^2 \left( \frac{\lambda_{\text{max}}}{\lambda} \right) \right] \quad (1.1)$$

where $p_{\text{max}}$ is the maximum polarization and $\lambda_{\text{max}}$ is the wavelength at which maximum polarization occurs (Serkowski et al., 1975). The parameter $K$ controls the opening of the curve and is given by Whittet et al. (1992) as
\[ K = 0.01 + 1.66 \lambda_{\text{max}} \text{ [\mu m]} \] (1.2)

Interstellar polarization from the ISM peaks in the green part of the visible spectrum (\sim 550 nm) (Serkowski et al., 1975; Draine, 2003). Dust grains predominantly scatter light forward along the direction of light propagation. Dust scattering from large grains produces gray (wavelength–independent) extinction (Draine, 2003) and achromatic scattering (Agol et al., 2003). For example, zodiacal light consists of an optical spectrum that is identical to that of the Sun. Zodiacal light is produced by sunlight scattering off large interplanetary dust grains, 10–100 \mu m in size (Leinert et al., 1998).

Light scattered at neutral and ionized gas particles produces wavelength–dependent linear polarization, with amplitudes that increase dramatically at the resonance frequency of the atomic transition. In the case of Rayleigh scattering, the particles are much smaller than the wavelength of light (< 10%). The Rayleigh size limit is parameterized as \( x = 2\pi a/\lambda \ll 1 \), where \( a \) is the radius of the grain and \( \lambda \) is the wavelength of the light. The scatterers (atoms or molecules of gas) act like dipole antennae which radiate perpendicular to the the plane of the incident light. Rayleigh scattered light is maximally polarized in a direction 90° from the direction of the incoming radiation. Earth’s blue sky is a result of Rayleigh scattering at air molecules (primarily nitrogen and oxygen) which preferentially scatter blue (\sim 450 nm) light\(^\dagger\).

In this work, I focus on polarization that arises from coherent scattering from an initial atomic state that is unpolarized to final state that is the same as the initial state, a process known as Rayleigh or resonant scattering Stenflo et al.\(^\dagger\)

\(^{\dagger}\)Online http://hyperphysics.phy-astr.gsu.edu/hbase/atmos/blusky.html#c2
I do not address coherent scattering from an initial unpolarized state to a final state that is *different* than the initial state, known as Raman or fluorescent scattering. By “resonant”, I mean scattering that occurs near a resonance (such as Hα); the term “Rayleigh” is more general and covers scattering at any distance from the resonance. I use the term “coherent” to mean a scattering process that is not disturbed by collisions, so the wavelength and phase of the initial radiation are preserved in the scattered radiation.

The optical depth of the scattering material can affect the observed polarization. Single scattering dominates in regions with low optical depth ($\tau < 1$). In these regions, on average, a photon scatters once while traversing the medium. It is easier to deduce the geometry of an asymmetric distribution of scattering material when the scattering occurs in regions with low optical depth. In this case, the scattering behavior may be well-described by relatively simple models of the system.

Optically thick asymmetric geometries may attenuate or enhance the degree of polarization compared with polarization observed from optically thin geometries. For example, a rotation of the polarization position angle (from perpendicular to parallel) may be seen in scattering geometries with an optically thick dusty equatorial disk and a less dense dusty “envelope”, especially when the system is viewed edge-on (Whitney and Hartmann, 1992). A similar scenario may be observed for Thomson scattering in geometrically thick gaseous equatorial disk geometries with high opacity. A position angle flip of 90° occurs because the polarization is dominated by singly scattered photons from the polar regions, producing a net negative polarization aligned parallel to the disk (e.g. Wood et al., 1996a, Fig 6a, $i = 60^\circ$). Hoffman et al. (2003) found slight negative polarization ($Q < 0$) produced by singly scattered photons at high inclinations ($i = 70^\circ$) when the photons scattered once in
the high latitudes of a geometrically thick disk before reaching the observer (disk opening angle $\alpha = 33^\circ$).

In addition to linear polarization, circular polarization has been observed in optically thick asymmetric circumstellar dust distributions, such as an asymmetric nebula or a disk surrounding a Young Stellar Object (YSO) (Martin, 1972; Menard et al., 1988). Models have shown that non-aligned grains in circumstellar environments produce low levels of circular polarization ($< 1\%$) (Whitney and Hartmann, 1992; Voshchinnikov and Karjukin, 1994; Whitney and Wolff, 2002). Circumstellar environments with non-spherical grains aligned by magnetic fields, radiation or stellar winds can produce high levels ($\pm 25\%$ to $40\%$) of circular polarization (Whitney and Wolff, 2002). Grain alignment in optically thick circumstellar distributions can also affect observed linear polarization because of the competing effects of scattering and differential extinction due to the dichroic grains (Whitney and Wolff, 2002). Differential extinction arises when dichroic grains are aligned because light with different polarization is absorbed in different amounts depending upon the direction of the alignment axis.

This thesis considers linear polarization resulting from starlight scattered at gas, dust and electrons from both optically thin and optically thick stellar and disk atmospheres. Échelle SpectroPolarimetric Device for the Observation of Stars (ESPaDOnS) observations did not reveal circular polarization in lines (Chapters 2 through 5). ESPaDOnS spectropolarimetric observations included all 4 Stokes parameters (see below). The broadband observations described in Chapter 6 produced Stokes $Q$ and Stokes $U$ data; no Stokes $V$ measurements were made. Please see each chapter for a description of the instruments involved and data reductions employed.
1.5 Spectropolarimetry

Spectropolarimetry is the combination of spectroscopy and polarimetry. Spectroscopy measures flux density as a function of radiation wavelength. The resulting spectrum can be used to characterize many parameters of a source, including its temperature. Polarimetry measures the degree of polarization (amplitude and position angle) of the light. The combined intensity and polarization spectra provide a complete description of the light observed from a source.

Linear polarization is described by the Stokes parameters $Q$ and $U$ which are calculated by measuring the difference in the intensity of light using a polarized filter oriented at two angles relative to north on the sky. Two sets of measurements are required, each set oriented along two orthogonal directions. The total intensity of light, Stokes $I$, is the sum of intensities measured at two orthogonal directions. Circular polarization is described by the Stokes $V$ parameter. The total intensity, linear polarization and circular polarization of light are described by the Stokes vector $[I, Q, U, V]^T$ where the Stokes parameters are calculated as follows.

\[
\begin{align*}
I &= I(0^\circ) + I(90^\circ) \\
Q &= I(0^\circ) - I(90^\circ) \\
U &= I(45^\circ) - I(135^\circ) \\
V &= \text{RHC} - \text{LHC}
\end{align*}
\] (1.3)

Here $I$ is the intensity of the light measured at each angle and RHC stands for the intensity of right–hand circular light and LHC stands for the intensity of left–hand circular light measured using filters.
Linear polarization is often described as a percent of the total intensity and is calculated from Stokes $Q$ and Stokes $U$ (which are also sometimes normalized by total intensity and described as a percent).

$$P = \sqrt{Q^2 + U^2}$$

$$\%p = \frac{P}{I} \times 100$$

$$\%q = \frac{Q}{I} \times 100$$

$$\%u = \frac{U}{I} \times 100$$

Here $I$ is total intensity, $Q$ is Stokes $Q$, $U$ is Stokes $U$ and $P$ is the degree of linear polarization.

The position angle (PA) of the linearly polarized light is described by an angle oriented east of north on the sky and is calculated as follows.

$$\Theta = \frac{1}{2} \tan^{-1} \left( \frac{U}{Q} \right)$$

Here $Q$ is Stokes $Q$, $U$ is Stokes $U$ as above and $\Theta$ is the position angle.

I adopt the conventions described in Bagnulo et al. (2009) for the treatment of position angle (PA). In this treatment, PA varies between 0° and 180°. Because linear polarization is a pseudo–vector, each angle has an equivalent angle at the measured PA minus 180°. For example, in the Bagnulo et al. treatment, 0° and 180° are equivalent. See Chapter 2 for more detail about the specific algorithm employed in this thesis.

### 1.6 Archive search for analog systems

The ε Aurigae Hα line profile is variable both in– and out–of–eclipse (e.g. Schanne, 2007; Mauclaire et al., 2012). The line consists of a central absorption superimposed
over a wide emission feature (Fig 1.4). The absorption is centered on the line rest wavelength (in the F0 star frame of reference), but the line core is often red– or blue–shifted somewhat from the line rest wavelength likely due to F0 star photospheric motion. The emission profile appears as red and blue emission wings and the strength of the wings is also variable. Linear polarization is associated with line core absorption out–of–eclipse (Harrington and Kuhn, 2009; Geise et al., 2012). I conducted an archival study to determine if Hα emission and linear polarization are common for spectral type F supergiant stars in an effort to better understand the evolutionary status of the primary star.

I observe Hα emission in archived spectra of known F supergiant stars when the stars are confirmed evolved (post–AGB) stars. F supergiant stars not classified as post–AGB do not show Hα emission, except perhaps for b Vel. Well–known F supergiant stars such as φ Cas, α Per and α Lep do not exhibit Hα emission (Table 1.1). The sample of F supergiant stars suggests that Hα emission is not common for this spectral type unless mass loss has occurred, evidenced by the post–AGB designation and/or the presence of circumstellar material. ε Aurigae is unusual for its spectral class because it exhibits Hα emission and the presence of circumstellar material is not confirmed.

1.6.1 Catalogs searched

I identified more than 20 high luminosity supergiant stars of spectral type F. The sample included a few hotter spectral type A supergiant stars because ε Aurigae is sometimes classified A8Ia. I searched the Canadian Astronomy Data Centre (CADC) archives\(^2\) for Échelle SpectroPolarimetric Device for the Observation of

Stars (ESPaDOnS) and the Telescope Bernard Lyot NARVAL archives\(^3\) for observations of these stars. ESPaDOnS and NARVAL are similar échelle instruments with spectral resolution of \(\sim 65,000\) (Donati et al., 2006). More than a dozen F stars have been observed with ESPaDOnS. Normalized intensity and Stokes \(V\) were archived for most of the stars; Stokes \(Q\) and \(U\) were archived for a few stars. Spectra were archived for a few F stars observed with NARVAL. The NARVAL archive included Stokes \(Q\) and Stokes \(U\) for very few of the candidate stars.

I obtained spectra for several spectral type F stars from the Ultra-violet and Visible Échelle Spectrograph (UVES) Paranal Observatory Project (POP) archive\(^4\) (Bagnulo et al., 2003). Observations were taken by the high-dispersion UVES instrument (300 nm to 1100 nm with a maximum spectral resolution 110,000) on a 8.2 meter diameter Unit Telescope (UT) from the European Space Agency (ESO) Very Large Telescope (VLT) installation. Spectropolarimetric data are not included in the UVES POP archive. The UVES spectral resolution is about 80,000 in the \(V\) band and the typical signal–to–noise ratio (S/N) is 300–500.

I also obtained spectra catalogued by Davies et al. (2005) from the Anglo–Australian Telescope (AAT). The resolution of the observations is 1.1 Å and the signal–to–noise is about 700. For more information, see the Visier catalogue\(^5\).

1.6.2 \(\text{H}\alpha\) emission

The \(\text{H}\alpha\) transition is usually observed in absorption in spectra of F supergiant stars. Figure 1.5 illustrates the \(\text{H}\alpha\) absorption profile for two F supergiant stars

---

\(^3\)Online at http://tblegacy.bagn.obs-mip.fr

\(^4\)Online at http://www.eso.org/sci/observing/tools/uvespop.html

\(^5\)Online at http://vizier.u-strasbg.fr/viz-bin/VizieR
sometimes used as templates for $\varepsilon$ Aurigae in spectral analysis. A very broad absorption feature is present in both supergiant stars $\alpha$ Lep (F0Ib) and $\alpha$ Per (F5Ib). The spectra are normalized to 1 in the continuum; note the wings have not yet returned to the continuum level in these plots. The absorption feature is broadened by Doppler motion in the extended atmosphere in both stars. Compare the H$\alpha$ profile for these stars to $\varepsilon$ Aurigae (Fig. 1.4).

I observe H$\alpha$ emission in archival spectra of five stars: LN Hya, V814 Her, 89 Her, V382 Aur and b Vel. The stars LN Hya, V814 Her, 89 Her and V382 Aur are listed as very likely post-AGB objects in the Toruń database\(^6\) (Szczerba et al., 2007) and are not candidate analog systems for $\varepsilon$ Aurigae because the presence of circumstellar dust is likely in these evolved systems. The supergiant star, b Vel, is not a post–AGB object and is not listed in the Toruń catalogue. b Vel is a candidate analog system for $\varepsilon$ Aurigae (below).

LN Hya (HR 4912, F3Ia) is a semi-regular evolved (post-AGB) star. LN Hya exhibits a variable H$\alpha$ profile (e.g. Klochkova and Panchuk, 2012) (see also Fig. 1.7). V814 Her (HD 161796, F3Ib) is a semi-regular pulsating evolved (post-AGB) star. Archived observations of V814 Her also indicate this star has a variable H$\alpha$ profile (Fig. 1.8). The semi-regular pulsating star, 89 Her (HD 163506, F2Ibe), displays a P Cygni-like H$\alpha$ line profile and significant linear polarization features associated with the H$\alpha$ absorption (Fig 1.9).

V382 Aur (HD 46703, F7IVw) is a high-latitude metal-poor post-AGB star with H$\alpha$ emission features (Fig. 1.10). Hrivnak et al. (2008) demonstrated that HD 46703 is a single-line spectroscopic binary with a period of 600 days, a systemic radial ve-

---

\(^6\)Online at https://fox.ncac.torun.pl/camkweb/postagb2.php
locity of $-94$ km s$^{-1}$, an orbital eccentricity of 0.3, and pulsation period of 29 days. The stellar abundances indicated that HD 46703 is a depleted star with abundance peculiarities attributed to the chemical fractionation of refractory elements and re-attribution of volatiles. The system is surrounded by a dusty and evidently stable circumbinary disk. The SED shows a large IR excess with a dust excess starting near the sublimation temperature (De Ruyter et al., 2006).

b Vel (HD 74180, F3Ia) is a possible analog system for ε Aurigae because it exhibits both absorption and emission in Hα and unlike AGB stars, b Vel does not have a large IR excess from circumstellar dust (Stencel et al., 1989, 0.71 Jy at 60 µm, Table II). Forbes and Short (1994) placed the spectral type at F0Ia ($M_{bol} = -8.9$) and determined that HD 74180 may be part of a physical subgroup of Vela OB1. They also suggested that the star is evolving blueward from the red giant phase after a period of enhanced mass loss. The Hα line is variable and may exhibit emission in the blue wing (Fig. 1.6).

Steemers and van Genderen (1986) found light variability in b Vel of $\sim 0.06$ in V band (or $\sim 0.15$ in $U$ band) on a rough time scale of $\sim 90$ days, and a variation in colors of $\sim 0^m 0.2$. They placed the distance at 1.7 kpc, determined a mass of $\sim 20$ $M_\odot$, $\log g \sim 1.1$, age $t \sim 7 \times 10^6$ yr, and deduced that the star has an extended gaseous envelope. Paredes et al. (1998) found significant variability in Ca ii H & K, Hδ, and Hγ. An IUE spectrum (1980–Mar–19) indicated asymmetric absorption associated with a stellar wind in Fe ii ($\lambda 2586$Å), but no wind or chromospheric emission features in Mg ii ($\lambda 2796$Å) (Snow et al., 1994). These authors adopted $M = 27M_\odot$, $R = 360.9R_\odot$. Stencel et al. (1989) noted a faint extended dust shell from IRAS data.
1.6.3 Linear polarization

I found Stokes $Q$ and Stokes $U$ data for four of the observed stars with H$\alpha$ emission wings. LN Hya and V814 Her exhibited no significant ($\geq 4 \sigma$) polarization associated with the line core of H$\alpha$ or any other spectral line for the epochs observed. V382 Aur displayed a broad loop in a $QU$-plot of the H$\alpha$ line. 89 Her exhibited many significant polarization features associated with absorption lines. All of these objects are likely post–AGB stars and may have circumstellar material.

1.6.4 Results of archive search

An archival study of spectral type F stars suggests that H$\alpha$ emission is not common for this spectral type. The prevalence of linear polarization in these systems is still unknown because too few Stokes $Q$ and Stokes $U$ spectra were archived for the stars in the study. A next step is to observe candidate analog systems like b Vel in Stokes $Q$ and Stokes $U$ to determine if linear polarization is present. This analysis may answer questions such as the following. How common are atmospheric asymmetries in evolved supergiant stars? Is asymmetry in the stellar atmosphere correlated with mass loss in the later evolutionary stages of these stars? Supergiant stars may be supernovae progenitors. Does an asymmetry in the stellar atmosphere of an evolved supergiant star lead to certain classifications of supernovae? In addition to these questions, a similar study of irregularly and non–radially pulsating stars may expand our understanding of asymmetries in their stellar envelopes.

1.7 Outline of dissertation

1.7.1 Thesis

My fundamental premise is that the $\varepsilon$ Aurigae system consists of an evolved F supergiant star, its B star binary companion and a disk of gas and dust that
originated from the F star. The disk originated from mass loss before the F star migrated off the main sequence. The star was an earlier spectral type, perhaps an O star, before leaving the main sequence. The disk is sustained by on-going low level mass transfer and possible companion star variability. F star pulsation helps to lift material to altitudes high enough for mass loss to occur.

Some features of the F star are unusual for the spectral type. I believe they are related to the advanced evolutionary status of the system. For example, spectropolarimetric observations show persistent anisotropies in the F star atmosphere. I believe that these anisotropies arise from non-radial pulsation modes and may be related to instabilities associated with the star’s post–main sequence evolutionary status.

1.7.2 Method

I employed a differential analysis of the $\varepsilon$ Aurigae system to isolate each component’s contribution to the observed spectral and polarimetric signal. The method consisted of the following steps:

1. Characterize F star spectral and polarization features out-of-eclipse

2. Remove the stellar contribution to characterize the disk spectrum and polarization

3. Look for unique features, such as wind signatures

1.7.3 Results

In Chapter 2, I present an abbreviated spectral time series for specific lines of interest with epochs chosen to highlight key orbital phases. The lines were chosen because they were previously discussed in the literature by observers over several
eclipse cycles. The “popularity contest” winning lines already illustrate many attributes of line polarization explored by this study such as (1) linear polarization is associated with the line core \((0 \pm 25 \text{ km s}^{-1})\) in out–of–eclipse spectra and (2) linear polarization resulting from F0 star light interacting with the disk material is associated with velocity–shifted absorption features as the eclipse progresses. The line absorption is first red–shifted and then blue–shifted during eclipse because the gas is rotating in the disk. The polarization follows the absorption observed in the spectra and the peak polarization is generally where the deepest absorption occurs in the line. This early work also highlights the presence of a persistent asymmetry in the photosphere of the primary F0 star. The paper is included in a special edition of the Journal of the American Association of Variable Star Observers (JAAVSO) commemorating the international scientific community’s response to the recent (2009–2011) eclipse.

I present a more detailed time series analysis of absorption and scattered light for select lines with significant polarization in Chapter 3. The paper is included in the conference proceedings from an International Astronomical Union symposium\(^7\) held in Costa Rica Nov. 30 to Dec. 5, 2014.

In Chapter 4, I detail the results of an analysis of significant \((> 4\sigma)\) polarization in out–of–eclipse (OOE) spectra. I identify and characterized the atomic transitions that produce significant linear polarization observed in 11 ESPaDOnS OOE spectra. The paper has been reviewed by collaborators.

Chapter 5 consists of the most detailed review ever created to address linear polarization arising from scattering in absorption lines during the recent (2009–2011)

\(^7\)Retrieved online 04/10/15 https://www2.hao.ucar.edu/events/IAUS305
$\varepsilon$ Aurigae eclipse. The $\varepsilon$ Aurigae spectra consist of over 500 absorption features. Eighty-three lines (5 are blends) show significant linear polarization and gas rotation signatures through the line. The imprint of gas rotation is found in early eclipse in $\text{H}\alpha$; most lines show the effect after mid–eclipse.

I present a study of archival and new medium–resolution spectropolarimetric observations in Chapter 6. These observations are important because they show out–of–eclipse continuum polarization variability. This work employs two different methods to remove interstellar polarization from the polarization measurements to reveal the underlying intrinsic polarization and its position angles for the first time.

A summary of important findings from this dissertation may be found in Chapter 7.
Table 1.1: F Star Archive Spectra.

<table>
<thead>
<tr>
<th>Target</th>
<th>Spectral Type</th>
<th>Object Type</th>
<th>Hα Emission</th>
<th>Line Pol</th>
<th>Archive</th>
</tr>
</thead>
<tbody>
<tr>
<td>φ Cas</td>
<td>F0Ia</td>
<td>SG</td>
<td>No</td>
<td>⋮</td>
<td>1, 2</td>
</tr>
<tr>
<td>HD 10494</td>
<td>F5Ia</td>
<td>SG</td>
<td>No</td>
<td>⋮</td>
<td>1, 2</td>
</tr>
<tr>
<td>HD 18369</td>
<td>A5Ib</td>
<td>SG</td>
<td>No</td>
<td>⋮</td>
<td>5</td>
</tr>
<tr>
<td>α Per</td>
<td>F5Ib</td>
<td>SG</td>
<td>No</td>
<td>⋮</td>
<td>1, 2</td>
</tr>
<tr>
<td>CE Cam</td>
<td>A0Iab</td>
<td>SG</td>
<td>Variable</td>
<td>⋮</td>
<td>1</td>
</tr>
<tr>
<td>HD 27290</td>
<td>F1V</td>
<td>Var</td>
<td>No</td>
<td>⋮</td>
<td>5</td>
</tr>
<tr>
<td>α Lep</td>
<td>F0Ib</td>
<td>SG</td>
<td>No</td>
<td>⋮</td>
<td>1</td>
</tr>
<tr>
<td>HD 37227</td>
<td>F0II</td>
<td>G</td>
<td>No</td>
<td>⋮</td>
<td>5</td>
</tr>
<tr>
<td>V382 Aur</td>
<td>F7Ivw</td>
<td>pAGB</td>
<td>Yes</td>
<td>Yes</td>
<td>1</td>
</tr>
<tr>
<td>PS Gem</td>
<td>F5Iab</td>
<td>pAGB</td>
<td>Yes</td>
<td>Yes</td>
<td>1</td>
</tr>
<tr>
<td>δ CMa</td>
<td>F8Iab</td>
<td>SG</td>
<td>No</td>
<td>⋮</td>
<td>1</td>
</tr>
<tr>
<td>CY Cmi</td>
<td>F5Iab</td>
<td>pAGB</td>
<td>Yes</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>HD 57167</td>
<td>F2III/IV</td>
<td>Binary</td>
<td>No</td>
<td>⋮</td>
<td>5</td>
</tr>
<tr>
<td>α CMi</td>
<td>F5I-V</td>
<td>Binary</td>
<td>No</td>
<td>2</td>
<td>1, 2</td>
</tr>
<tr>
<td>HD 62623</td>
<td>A3Iab</td>
<td>SG+disk</td>
<td>Yes</td>
<td>⋮</td>
<td>5</td>
</tr>
<tr>
<td>HD 67523</td>
<td>F8II</td>
<td>Var</td>
<td>⋮</td>
<td>⋮</td>
<td>5</td>
</tr>
<tr>
<td>b Vel</td>
<td>F3Ia</td>
<td>SG</td>
<td>Variable</td>
<td>⋮</td>
<td>1</td>
</tr>
<tr>
<td>HD 80404</td>
<td>A8Ib</td>
<td>SG</td>
<td>No</td>
<td>⋮</td>
<td>5</td>
</tr>
<tr>
<td>ρ Leo</td>
<td>B1Iab</td>
<td>SG</td>
<td>No</td>
<td>⋮</td>
<td>1</td>
</tr>
<tr>
<td>V533 Car</td>
<td>A6Ia</td>
<td>SG</td>
<td>Yes</td>
<td>⋮</td>
<td>4, 5</td>
</tr>
<tr>
<td>HD 101584</td>
<td>F0Iape</td>
<td>pAGB</td>
<td>Yes</td>
<td>⋮</td>
<td>5</td>
</tr>
<tr>
<td>V810 Cen</td>
<td>F9Ia</td>
<td>SG</td>
<td>Binary?</td>
<td>⋮</td>
<td>⋮</td>
</tr>
<tr>
<td>V1123 Cen</td>
<td>F4Ib/II</td>
<td>pAGB</td>
<td>Yes?</td>
<td>Possible</td>
<td>1</td>
</tr>
<tr>
<td>HD 108968</td>
<td>F7Ib/II</td>
<td>Cepheid</td>
<td>No</td>
<td>⋮</td>
<td>5</td>
</tr>
<tr>
<td>LN Hya</td>
<td>F3Ia</td>
<td>pAGB</td>
<td>Variable</td>
<td>No</td>
<td>1</td>
</tr>
<tr>
<td>V814 Her</td>
<td>F3Ib</td>
<td>pAGB</td>
<td>Variable</td>
<td>No</td>
<td>1</td>
</tr>
<tr>
<td>89 Her</td>
<td>F2Ibe</td>
<td>pAGB</td>
<td>P Cygni</td>
<td>Yes</td>
<td>1</td>
</tr>
<tr>
<td>AC Her</td>
<td>F4Ibpv</td>
<td>pAGB</td>
<td>Variable?</td>
<td>Yes</td>
<td>1</td>
</tr>
<tr>
<td>ν Aql</td>
<td>F2Iab</td>
<td>SG</td>
<td>No</td>
<td>⋮</td>
<td>1, 2</td>
</tr>
<tr>
<td>η Aql</td>
<td>F6Iab</td>
<td>SG</td>
<td>No</td>
<td>⋮</td>
<td>1</td>
</tr>
<tr>
<td>V5112 Sgr</td>
<td>F2/F3Iab+</td>
<td>pAGB</td>
<td>Yes</td>
<td>Possible</td>
<td>1</td>
</tr>
<tr>
<td>γ Cyg</td>
<td>F8Iab</td>
<td>SG</td>
<td>No</td>
<td>⋮</td>
<td>1, 2</td>
</tr>
<tr>
<td>α Cyg</td>
<td>A2Iae</td>
<td>SG</td>
<td>P Cygni</td>
<td>⋮</td>
<td>1</td>
</tr>
</tbody>
</table>

Continued on Next Page...
Table 1.1 – Continued

<table>
<thead>
<tr>
<th>Target</th>
<th>Spectral Type</th>
<th>Object Type</th>
<th>Hα Emission</th>
<th>Line Pol</th>
<th>Archive</th>
</tr>
</thead>
<tbody>
<tr>
<td>δ Cep</td>
<td>F5Iab</td>
<td>Cepheid</td>
<td>No</td>
<td>...</td>
<td>1</td>
</tr>
<tr>
<td>6 Cas</td>
<td>A3Iae</td>
<td>SG</td>
<td>P Cygni</td>
<td>...</td>
<td>3</td>
</tr>
</tbody>
</table>

*aObject type: Giant (G), post–AGB (pAGB), supergiant (SG), Variable star (Var)*

*bArchives: (1) ESPaDOnS, (2) NARVAL, (3) ELODIE, (4) AAT, (5) UVES POP*
Figure 1.1: Artist rendering of the ε Aurigae system. Every 27 years, the bright star called Epsilon Aurigae fades over a period of two years, then brightens back up again. The companion is surrounded by a dusty disk, as illustrated in this artist’s concept (not to scale). A model of the spectral energy distribution (SED) suggests that the objects in the system are an F0 star (the primary source of visible light) and a dusty disk surrounding a B5V star (Hoard et al., 2010, 2012). Interferometric images show the tilted eclipsing opaque disk moving in front of the F star (Kloppenborg et al., 2010). Artist’s concept image credit: NASA/JPL-Caltech
Figure 1.2: A top–down view of two orbital solutions for ε Aurigae. The low mass scenario, $q = 0.75$ (top) and high mass scenario, $q = 1.25$ (bottom) are shown. F0 star orbit (green), B star orbit (blue) and disk (gray) are to scale. The line marks the line–of–sight to Earth, shown at mid–eclipse. Each star orbits the center of mass (X) in 27 years. The more massive star occupies the smallest orbit in each figure.
Figure 1.3: Mass loss across the HR diagram (de Jager et al., 1988). The 3 blue circles represent spectral type F supergiants used in their analysis. 89 Her (post–AGB) is the lone blue circle at log $L/L_\odot = 4.0$. Red circles represent two solutions for $\epsilon$ Aurigae from the literature. Hoard et al. (2010) assumed the F star was a post-AGB object and derived log $L/L_\odot = 4.7$ while fitting an SED to the system components; Castelli (1978) assumed an F0 supergiant star and derived log $L/L_\odot = 5.1$ in her fine analysis of the $\epsilon$ Aurigae spectrum. The present day mass loss rate is estimated at $\dot{M} \approx 10^{-7} M_\odot \text{ yr}^{-1}$.
Figure 1.4: Hα line profile and linear polarization in an out-of-eclipse ESPaDOnS spectrum of ϵ Aurigae. The line is variable and consists of absorption superimposed over a broad emission feature. The data have been rotated into the stellar/disk reference frame and corrected for F0 star stellar motion. Normalized intensity is plotted with velocity in km s\(^{-1}\), centered on the laboratory rest wavelength of the line (top). Percent polarization (\(\%p\)) is plotted with velocity (bottom). Blue diamonds indicate S/N ≥ 4σ, green asterisks indicate S/N ≥ 3σ. The polarization is slightly blue shifted from line center and the line has a small blue shifted additional absorption that may be a photospheric F0 star feature.
Figure 1.5: Hα line profiles of the supergiants HD 36673 (α Lep, F0Ib) and HD 20902 (α Per, F5Ib). Both objects are classified as spectral type F supergiant stars. These Ib supergiants are slightly less luminous than ε Aurigae (F0Ia) and α Per at F5 is slightly cooler than than ε Aurigae. Both spectra have been adjusted for stellar motion so that the absorption feature is centered at the line rest wavelength (Hα 656.280 nm). The wide absorption wings extend beyond the plotting range; the continuum is normalized to 1 in both spectra. The small absorption feature in the blue wing (−150 km s⁻¹) arises from Earth’s atmosphere (telluric). There are no Hα emission features present in these spectra. Compare these Hα intensity profiles to ε Aurigae (Fig. 1.4).
Figure 1.6: b Vel (HD 74180, F3Ia) Hα line profiles of the supergiant star for two epochs about a year apart. This star is a candidate analog system for ε Aurigae (see text). The ESPaDOnS spectra have been adjusted for systemic radial velocity. The deepest part of the Hα line is not at line center; the system may be a binary or the spectra may indicate a stellar wind is present (inverse P Cygni profile). Note the variability in the Hα line profile, especially a possible blue wing emission feature that does not rise above the continuum. Further discussion about the evolutionary status of this star may be found in Forbes and Short (1994).
Figure 1.7: LN Hya (HR 4912, F3Ia) Hα line profile. Normalized intensity is plotted with velocity in km s\(^{-1}\), centered on the laboratory rest wavelength of the line. The data have been corrected for stellar motion. Note the emission wings. This star was listed as very likely post-AGB in the Toruń catalogue. No linear polarization data were archived.
Figure 1.8: V814 Her (HD 161796, F3Ib) Hα line profiles for this post–AGB object for two epochs, 2005–08–22 and 2009–02–16. The spectra have been adjusted for stellar motion. Note the variability in the line profile. The central absorption is deeper and more symmetric in the first observation and a blue-shifted emission wing is more pronounced in the second observation. Also note the slight asymmetry in the red-shifted absorption near line center in the second epoch. There were no significant ($\geq 4\sigma$) polarization features associated with the line in either epoch.
Figure 1.9: 89 Her (F2Ibe) line profile and linear polarization spectrum. The data have been corrected for stellar motion. Normalized intensity is plotted with velocity in km s$^{-1}$, centered on the laboratory rest wavelength of the line in the upper plot. Percent polarization is plotted with velocity on the lower plot. Blue diamonds indicate S/N $\geq 4\sigma$, green asterisks indicate S/N $\geq 3\sigma$. This star is listed as very likely post-AGB in the Toruń catalogue.
Figure 1.10: V382 Aur (F7IVw) Hα line profile. V382 Aur is a low-metallicity post-AGB star. This is a spectroscopic binary system with a circumbinary dust shell and spectral features indicate the star is depleted (Hrivnak et al., 2008). The data have been corrected for stellar motion. Normalized intensity is plotted with velocity in km s$^{-1}$, centered on the laboratory rest wavelength of the line (top). QU-plot of polarization in the Hα line (bottom). Line core (green asterisks), red wing (red asterisks) and blue wing (blue asterisks) are indicated. Very likely post-AGB Toruń catalogue.
Chapter 2

Eclipse Spectropolarimetry of the ε Aurigae System

2.1 Summary

The recent eclipse of the enigmatic binary star system, ε Aur, offered a special opportunity to explore the role of spectropolarimetry in discovery of unknown facets of the objects involved. Here we present spectropolarimetric results for H–alpha, H–beta, Ca i (422.6 nm), and K i (769.9 nm) based on 51 epochs of high dispersion spectra obtained with the ESPaDOnS instrument at CFHT during 2006–2012.

2.2 Introduction

The target, ε Aur, is a single line spectroscopic binary that features an opaque disk, surrounding a hidden companion, that causes a lengthy eclipse every 27 years – for a reading list, see, for example, Stencel et al. (2011). Instrumentation advances of the past decade have enabled a remarkable set of new spectropolarimetric data to be obtained during the 2008–2011 eclipse. The ESPaDOnS instrument (Donati, 2003) at the Canada–France–Hawai‘i Telescope obtained more than 50 epochs of full Stokes polarimetry from 3800Å to 10000Å. Prior efforts have revealed broadband polarization changes during eclipses, successfully predicting some disk characteristics, as well as demonstrating post–eclipse variability (Kemp et al., 1986; Cole, 2012). Spectropolarimetric observations may contribute to our understanding of the system by revealing the nature and distribution of gaseous material in the F–star atmosphere and in the occulting disk. This paper provides a description of data
analyzed to date. Our preliminary results indicate that the increased polarization observed in broadband during eclipse is also present in many spectrographic lines.

2.3 Observations

The data were obtained using the EPSaDOnS instrument at the Canada–France–Hawaii telescope (CFHT). ESPaDOnS is a cross-dispersed échelle spectropolarimeter designed to obtain a complete optical spectrum in a single exposure, with a resolving power of $\sim$65 000 (Donati et al., 2006). The $\varepsilon$ Aur data used in this report were obtained with about $10^6$ counts per spectral bin. The normalized intensity (normalized to 1) corresponds to an average uncertainty of about $1 \times 10^{-3}$, for a signal-to-noise (S/N) of c. 1000. All four Stokes parameters were taken for each observation (see Table 2.1 for a log of observations).

We retrieved ESPaDOnS observations of $\varepsilon$ Aur from the Canadian Astronomy Data Centre (CADC), CFHT Science Data Archive\(^1\). Fifty epochs of spectropolarimetric observations of $\varepsilon$ Aur span the time from pre–eclipse (beginning February 2006) through the eclipse phases and include post–eclipse observations (for example, January 2012). The data were automatically reduced with Upena, CFHTs reduction pipeline for ESPaDOnS. Upena uses LIBRE_ESPRIT, which is a proprietary data reduction software tool (Donati et al., 1997).

2.3.1 Contributions of polarimetry to the study of $\varepsilon$ Aur

Polarization signatures occur when symmetries are broken. Possible sources of polarization are rotation deformities, aspherical winds, tidal distortions in binary systems, the Chandrasekhar effect during eclipse of binary systems, photospheric inhomogeneities including radiation inhomogeneities, and matter streams or accretion.

\(^{1}\)online at http://www1.cadc-ccda.hia-iha.nrc-cnrc.gc.ca/cadc/
Polarization signatures due to scattering depend upon the nature and distribution of the scatterers: electrons, atomic species, and/or dust grains. Broadband polarization signatures (for example, see Cole (2012); Henson et al. (2012); Kemp et al. (1986); Coyne (1972)) may include contributions from both the continuum and lines that may involve different scattering agents.

The spectropolarimetric observations included in this paper reveal anisotropies in gaseous atomic species intrinsic to the F star, as well as geometric and/or scattering effects of the disk during eclipse. One possible geometric source of polarization in lines during eclipse is the Chandrasekhar effect associated with limb polarization of the F star. One possible source of polarization out–of–eclipse is anisotropy associated with stellar pulsation, for example. Our goal is to identify the source or sources of polarization in the lines both in– and out–of–eclipse revealed by these excellent ESPaDOnS high–resolution observations. ESPaDOnS observations cannot be used to measure continuum polarization\(^2\).

\(^2\)http://www.cfht.hawaii.edu/Instruments/Spectroscopy/Espadons/
2.4 Method

Linear polarization, $P$, was computed using normalized $Q$ and $U$ (that is, $Q/I_c$ and $U/I_c$) for each wavelength in the observation according to Equation (2.1) (Bag-nulo et al., 2009).

$$\frac{P}{I_c} = \sqrt{\left(\frac{Q}{I_c}\right)^2 + \left(\frac{U}{I_c}\right)^2}$$  \hspace{1cm} (2.1)

Percent linear polarization was calculated as follows

$$\%p = \frac{P/I_c}{I/I_c} \times 100\%$$  \hspace{1cm} (2.2)

Where $I/I_c$ denotes the normalized intensity. Percent $q$ ($\%q$), percent $u$ ($\%u$), and percent $v$ ($\%v$), where $q$, $u$, and $v$ are the normalized Stokes parameters, were calculated in a manner similar to Equation (2.2).

Assessing the true errors in polarimetric measurements is crucial to establishing the physics of the source. We assume that the Stokes parameters $Q$ and $U$ are normally distributed about their true values, but it has been shown that linear polarization follows a Rice distribution (for example, Clarke and Stewart (1986)).

The Rice probability distribution is given by

$$R(p|p_0,\sigma) = \frac{p}{\sigma^2} \exp\left[-\frac{p + p_0^2}{2\sigma^2}\right] I_0\left(\frac{pp_0}{\sigma^2}\right)$$  \hspace{1cm} (2.3)

Here $p_0$ is the underlying, true, polarization, $I_0$ is the zeroth-order modified Bessel function, and the underlying Gaussian noise has variance $\sigma^2$. In the limit of high signal–to–noise (S/N), the Rice distribution approaches the Gaussian (normal) distribution, with a mean that approaches $p_0$ and a standard deviation that
approaches \( \sigma \) Vaillancourt (2006). The Rice mean is given by

\[
\mu_R = \sqrt{\frac{\pi}{2}} \sigma L_{1/2} \left( \frac{-\mu^2}{2\sigma^2} \right) \tag{2.4}
\]

Here \( L_{1/2}(x) \) is a Laguerre polynomial of order \( 1/2 \), \( \mu \) is the mean, and \( \sigma \) is the standard deviation. The Rice variance is given by

\[
\frac{1}{2} \pi \sigma^2 L_{1/2}^2 \left( \frac{-\mu^2}{2\sigma^2} \right) \tag{2.5}
\]

Here \( L_{1/2}^2(x) \) is a generalized Laguerre polynomial \( L_{n}^{(\alpha)}(x) \) with \( n = 1/2 \) and \( \alpha = 2 \). The Rice standard deviation may be found by taking the square root of the variance.

By definition, the parameter \( p \) is a positive definite quantity. The individual polarization values calculated from Equation (2.1) will always be positive and non–zero because the individual values of \( Q \) and \( U \) will generally be non–zero. At large S/N \( (p/\sigma \geq 4) \) the maximum likelihood and most probable estimators for the linear polarization (for example, Simmons and Stewart (1985)) converge to

\[
\hat{p} = \sqrt{(p^2 - \sigma^2)} \tag{2.6}
\]

Equation (2.6) corrects for the positive bias in the linear polarization calculated using Equation (2.1) (Clarke, 2009). The data presented here are not corrected for interstellar polarization. The mean value of \( p \) may be computed using the mean values of \( q \) and \( u \) (Clarke and Stewart, 1986) as follows

\[
\bar{p} = \sqrt{(\bar{q}^2 + \bar{u}^2)} \tag{2.7}
\]

The barred variables denote the mean.
Linear polarization position angle, $\Theta$, may be computed from Stokes $q$ and $u$ as follows (Bagnulo et al., 2009). Position angles will range from 0 to 180 degrees.

$$\Theta = \frac{1}{2} \tan^{-1}\left(\frac{u}{q}\right) + \Theta_0$$

$$\Theta_0 = \begin{cases} 
0^\circ & \text{if } q > 0 \text{ and } u \geq 0 \\
180^\circ & \text{if } q > 0 \text{ and } u < 0 \\
90^\circ & \text{if } q < 0 
\end{cases}$$

$$\Theta = \begin{cases} 
45^\circ & \text{if } q = 0 \text{ and } u > 0 \\
135^\circ & \text{if } q = 0 \text{ and } u < 0 
\end{cases}$$

The ESPaDOnS data are noisier at shorter wavelengths (that is, toward the blue) than longer wavelengths because the detector is less sensitive in the blue. We binned the linear polarization data with a wavelength bin of 0.015 nm using the error-weighted mean (for example, Taylor (1997)) to boost signal–to–noise at shorter wavelengths and for deep absorption lines. We determined through trial and error that this was the largest bin size that did not seriously degrade the resolution of the line. In some cases, we combined several epochs (using the error–weighted mean) to further reduce noise prior to wavelength binning, using the criterion that the line profile did not change between binned epochs.

We computed the mean for both $q$ and $u$ using the binned data and then computed the mean linear polarization using Equation (2.7). The Rice mean and variance were computed for each $p$ using Equations (2.4) and (2.5), adopting the mean polarization for $\mu$ in those equations. Finally, we bias–corrected the linear polarization using Equation (2.6), adopting the Rice standard deviation for $\sigma$ in that equation. We adopted the error bars given in the pipeline reduction as the uncer-
tainty in both normalized intensity and normalized Stokes parameters and propa-
gated those uncertainties in calculations of percent Stokes (see, for example, error
bars in Figure 2.2). We also propagated the uncertainty (Rice standard deviation)
in the calculation of %p (see, for example, error bars in Figure 2.1).

For polarizations with large S/N, the confidence regions approach those given
by a normal Gaussian distribution centered on the bias-corrected value of p, with
2σ corresponding to 95% and 2.6σ corresponding to 99% confidence for p/σ ≥ 4
(Vaillancourt, 2006). The maximum likelihood estimator (Equation 6) of the under-
lying (“true”) polarization converges with all other estimators when p/σ is greater
than 4. For p/σ greater than 3 and less than 4, the maximum likelihood estimator
may not completely correct for bias; the polarization is considered the upper bound.
Values of p/σ less than 1.4 correspond to zero polarization (Vaillancourt, 2006).
We identified spectroscopic regions with significant linear polarization by flagging
polarization peaks for p/σ ≥ 4.

We rotated the unbinned data by 27 degrees using a rotation matrix (for example,
Code and Whitney (1995); Bagnulo et al. (2009)) to align instrument north with
the rotation axis of the system as described by Kloppenborg et al. (2010) before
binning by epoch and wavelength. We confirmed that the invariant, (Q^2 + U^2), was
conserved under rotation (intensity is unaffected by rotation and %p is unaffected as
long as the invariant is conserved). We verified that the null parameters provided by
the ESPaDOnS pipeline contained no signal, indicating that any instrument effects
were removed by the data reduction. We were also careful to change the sign of
Stokes U as directed by the ESPaDOnS FITS file headers.
2.5 Analysis

2.5.1 Linear polarization time series and QU–plots

Initial analysis focused on the stronger lines in order to assess whether the eclipse resulted in changes to the polarization. A sample time-series of H-alpha line profiles and polarizations are shown in Figure 2.1. A sample plot of $\%q$ vs. $\%u$ (a QU–plot) is shown in Figure 2.2. The error bars in the QU-plot are the $1\sigma$ propagated (assumed Gaussian) average uncertainties in both $\%q$ and $\%u$. The angle from the +$q$ axis measured counterclockwise to a feature in the QU–plot corresponds to twice the position angle ($2\theta$) as measured east of north and may be a useful diagnostic of the geometry of the scattering giving rise to the polarization. We were careful to exclude $\%q$ and $\%u$ contributions from neighboring lines in these plots when possible.

2.5.2 Hydrogen alpha

We fit the pre–eclipse H–alpha line (rest wavelength 656.280 nm) with a Gaussian function and adopted the HWHM of the Gaussian (c. 25 km s$^{-1}$) as the line core. We further defined the wings as follows: the blue wing ($-125$ km s$^{-1}$ to $-25$ km s$^{-1}$) and the red wing ($25$ km s$^{-1}$ to $125$ km s$^{-1}$). Regions outside of these defined areas consistently mapped to (0,0) in the QU–plots. These definitions are maintained throughout the following analysis.

H–alpha exhibited persistent polarization in the line core in all epochs (see Figure 2.1). During pre-eclipse, the line core accounted for a nearly linear excursion of ($-\%u,-\%q$) in the QU–plot (green diamond symbol, Figure 2.2). The line was largely symmetric, with both red and blue emission wings evident. The line appeared slightly broadened to the red when compared to the Gaussian function. The
blue and red emission wings exhibited no polarization features in this binned epoch, or in any pre-eclipse epoch. At no phase did the H–alpha line reach zero intensity.

Harrington and Kuhn (2009) noted the strong presence of spectropolarimetric signatures in and around the absorptive components of the H–alpha emission line in Herbig Ae/Be stars that they called “polarization–in–absorption”. They also identified a broad polarization signature across emission features for many classical Be stars in their sample. Herbig Ae/Be stars are embedded in cold gas and dust, which may be equatorially enhanced, whereas classical Be stars are rapid rotators characterized by ionized equatorial material. The equatorial material surrounding these two types of stars contributes to distinctly different polarization signatures. The polarization features we observed in pre–eclipse ε Aur spectra are similar to “polarization–in–absorption”; this suggests that ε Aur does not have an equatorial enhancement of ionized material.

At mid–eclipse, and for many epochs following mid–eclipse, the line exhibited a central emission feature (presumed recombination, see Stencel et al. (2011)). %p increased, consistent with changes to broadband polarization reported by Cole (2012) and Kemp et al. (1986). The core polarization peak appears notched in these epochs, possibly indicating a depolarization associated with the emission core. At mid–eclipse, the blue and red absorption wings exhibited broad %p polarization. There were excursions in the QU–plot for features in the line core (−%q; green diamond symbol), as well as the blue (+%q, +%u; blue square symbol) and red (+%q, −%u; red triangle symbol) absorption wings (Figure 2.2). These QU–plot excursions were not affected by binning and are evident in several observations around this time.
By late eclipse, the line exhibited a broad, deep, blue-shifted absorption. Normalized intensity dropped to about 10% at the deepest part of the line, but signal–to–noise remained above 700 and the ratio \( p/\sigma \) ranged from 3 to 25 for polarization greater than 0.4%, significant within the Rice statistics. The central core polarization remained strong (> 1%) in late eclipse, but the blue wing polarization increased (> 0.5% at \(-100 \text{ km s}^{-1}\)), while the red wing polarization decreased (that is, negligible at 100 km s\(^{-1}\)). In the QU-plot, the line core accounted for the \(-%q\) features (green diamonds), the blue wing accounted for the \(+%q\) features (blue squares), and the red wing polarization (red triangles) was largely concentrated at (0,0) (Figure 2.2). Thus, the polarization behavior followed the line behavior in this epoch.

The H–alpha line did not return to its pre–eclipse form by the time of our last post-eclipse observation (January 17, 2012). The red emission wing reappeared at about the pre–eclipse level, but the blue emission wing was masked by a broad (> \(-150 \text{ km s}^{-1}\)), shallow (normalized intensity c. 0.9) absorption. Line core polarization remained above 1% and the blue wing polarization feature disappeared. The line core polarization maintained a largely \(-%q, +%u\); green diamonds) orientation in the QU–plot (see the post-eclipse binned epoch presented in Figure 2.2).

Clearly, the passage of the rotating, dark disk in front of the F star induces polarization signals away from line center. Continuing observations may be able to demonstrate whether the persistent line core polarization tracks the F star or a disk–tied source velocity around the orbit.

\(^{3}\)The line returned to its pre–eclipse profile by the time of our observation 2012–12–09 (Fig. 5.22).
2.5.3 Hydrogen alpha polarization position angle

We calculated the position angle for ($%q$, $%u$) pairs for the H–alpha line in mid–eclipse (Figure 2.3). The data are rotated to the stellar frame and are not binned. Notice that the linear polarization position angle appears randomly scattered outside of the line, which is expected. The position angles that correspond to the line core ($\pm 25$ km s$^{-1}$ from rest wavelength) are plotted in green; position angles corresponding to the blue–shifted absorption wing ($-125$ km s$^{-1}$ to $-25$ km s$^{-1}$) are plotted in blue; and position angles corresponding to the red–shifted absorption wing ($+25$ km s$^{-1}$ to $+125$ km s$^{-1}$) are plotted in red. Position angles only range from 0° to 180° because of the nature of the Stokes parameters; a position angle of 180° is consistent with 0°. Notice the line core polarization is offset by about 90° from the wings. This may be an opacity effect. Compare these data to the mid–eclipse QU–plot (Figure 2.2).

2.5.4 Hydrogen beta

Unlike the pre–eclipse H–alpha line, the H–beta line (rest wavelength 486.135 nm) was better fitted by a Lorentzian profile and we adopted the HWHM of this profile (c. 35 km s$^{-1}$) as the line core. We further defined the wings as follows: the blue wing ($-125$ km s$^{-1}$ to $-35$ km s$^{-1}$) and the red wing (35 km s$^{-1}$ to 125 km s$^{-1}$) and noted that regions outside of the defined areas consistently mapped to (0,0) in the QU–plots. These definitions are maintained throughout the following analysis.

H–beta also exhibited persistent polarization in the line core in all epochs (see Figure 2.4). In pre–eclipse, the normalized intensity was at 13%, but the signal–to–noise remained above 1000. The ratio $p/\sigma$ was consistently greater than 4 for $\%p$ greater than 0.22%. The $-\%q$ excursion in the QU–plot (Figure 2.5) corresponds to line core polarization and differs in orientation from H–alpha pre–eclipse (see
The line itself appeared nearly symmetric and red-shifted by about the velocity of the F star at that phase.

The H–beta line maintained a deep and broad absorption at mid–eclipse that deepened further by late eclipse. \( \%p \) increased in mid– and late eclipse. At mid–eclipse, the normalized intensity fell to about 5% at the deepest part of the line, but signal–to–noise remained greater than 500. The linear polarization was greatest at the line core, with smaller contributions from the blue and red absorption wings. The ratio \( p/\sigma \) remained consistently greater than 4 for \( \%p \geq 0.2\% \) in this epoch. There were excursions in the QU–plot for features in the line core (\( −\%q \); green diamond), as well as the blue (\( +\%q, +\%u \); blue square) and red (\( +\%q, −\%u \); red triangle) absorption wings (Figure 2.5). These QU–plot excursions are similar to those exhibited by H–alpha for this epoch.

By late eclipse, the line exhibited a broad, deep, blue–shifted absorption. The line is clearly saturated in late eclipse, falling to just 1.6% intensity at the deepest point and, although S/N is nearly 200 here, the ratio \( p/\sigma \) is only 1.2; therefore \( \%p = 0 \). The ratio \( p/\sigma \) ranged from 3 to 11 for \( \%p > 0.4 \) outside the saturated region. The central core polarization appears to have decreased; the blue wing polarization (outside of the saturated region) increased (> 2% at \(-70 \text{ km s}^{-1}\)), while the red wing polarization decreased (c. 0.2% at 70 km s\(^{-1}\)) from mid–eclipse levels. In the QU–plot, the line core accounted for the \( −\%q \) features (\( p/\sigma \geq 3 \) at \(-20 \text{ km s}^{-1}\); \( p/\sigma \geq 4 \) at \(-10 \text{ km s}^{-1}\) and throughout the remainder of the core), the unsaturated blue wing accounted for the \( +\%q \) features (Figure 2.5; blue squares) and the red wing polarization was largely concentrated at (0,0). The polarization behavior also followed the line behavior in this epoch and qualitatively resembles the H–alpha polarization.
The H–beta line did not return to its pre–eclipse form by the time of our last post–eclipse observation (January 17, 2012)\textsuperscript{4}. The line was deeper, broader, and blue–shifted by about $-20 \text{ km s}^{-1}$ with a strong (c. 1.5\%), narrow polarization peak centered on this velocity. The line was deep, but unsaturated, with normalized intensity nearly 8\% and signal–to–noise above 500. The ratio $p/\sigma$ remained above 4 for $\%p$ greater than 0.5\%. The line core polarization maintained a largely $-\%q$ orientation in the QU–plot (see the post–eclipse binned epoch presented in Figure 2.5).

2.5.5 Hydrogen gamma and Hydrogen delta

In pre–eclipse, H–gamma (rest wavelength 434.047 nm) appeared to exhibit low–level polarization features, but there were insufficient data points corresponding to $p/\sigma \geq 4$. H–delta (rest wavelength 410.008 nm) in pre–eclipse showed no polarization features. By mid–eclipse, both lines became saturated, making analysis of line core polarization impossible. However, both lines exhibited absorption wing polarization meeting the $p/\sigma \geq 4$ criteria. These features exhibited excursions in the QU–plot of $+\%u$ for blue-shifted absorption and $-\%u$ for red-shifted absorption for both lines, which is consistent with both H–alpha and H–beta polarization during this epoch. The lines remained saturated in late eclipse and there were no significant polarization features post–eclipse for either line.

2.5.6 Potassium (769.896 nm)

The K\textsc{i} line (rest wavelength 769.896 nm) described here is the weaker line of a doublet that arises from the ground state. The out–of–eclipse line is thought to have an interstellar origin (Welty and Hobbs, 2001). The K\textsc{i} (769.896 nm) line exhibited no polarization signatures until after mid–eclipse. We identified no F star

\textsuperscript{4}The line returned to its pre–eclipse profile by the time of our observation 2012–12–09.
contribution; varying absorption and polarization features described below may be attributed to the disk.

In pre–eclipse, the line profile remained constant; the stellar radial velocity was red–shifted with respect to the line rest wavelength (see Figure 2.6); and no linear polarization features were observed (see examples, Figures 2.6 and 2.7). A Gaussian fit to the line profile returned a HWHM of 0.02 nm.

After first contact, the line exhibited a red–shifted (about 20 km s$^{-1}$) feature initially about the same depth as the line core (normalized intensity about 0.7) that deepened to a normalized intensity of about 0.3. There were no significant ($p/\sigma \geq 3$) polarization features evident until after second contact. The weak (c. 0.3%), narrow linear polarization feature that appeared after second contact was centered on the red–shifted component of the line.

By mid–eclipse the line appeared deeper and broader than during pre–eclipse epochs. A broad, weak ($< 0.2\%$) linear polarization feature appeared which was centered on the line (Figure 2.6). In Figure 2.6, the ratio $p/\sigma$ is greater than 3 for polarization above 0.1% and is greater than 4 for polarization above 0.15%; the polarization is significant by Rice statistics. The stellar radial velocity was not shifted with respect to the line rest wavelength at mid–eclipse.

The line developed a broad, blue–shifted component after mid–eclipse. Polarization remained low (below 0.2%) until late eclipse, when the line was very broad. We fit a Gaussian function to the late eclipse line profile; the fit yielded a HWHM of 0.05 nm, more than twice the HWHM measured in pre–eclipse. The Gaussian centroid corresponded to a shift of $-20$ km s$^{-1}$ from the rest wavelength. A larger
(c. 0.5%) polarization feature was centered on the blue–shifted component of the line in this epoch (see Figure 2.6), which corresponded to a ($-\%q$, $+\%u$; blue squares) loop in the QU–plot (Figure 2.7). The star’s radial velocity became blue–shifted with respect to the line rest wavelength after mid–eclipse.

The line retained a blue–shifted component after 4th contact that decreased in breadth and depth over time. There were no polarization features evident after 4th contact. The line had nearly returned to its pre–eclipse form by our last observation (January 17, 2012)\(^5\).

We examined the stronger line of the K\textsc{i} doublet, (rest wavelength 766.490nm) and discovered that it exhibited line profile and polarization variations similar to the weaker line. At late eclipse, the line exhibited a broad, blue–shifted absorption component. A linear polarization feature was centered on the blue–shifted component and the QU–plot also exhibited a ($-\%q$, $+\%u$) loop.

### 2.5.7 Calcium (422.673 nm)

The Ca\textsc{i} line (rest wavelength 422.673 nm) described here arises from the ground state and shows a persistent core polarization signature in pre–, mid– and late eclipse phases (Figure 2.8). The late eclipse polarization appeared dramatically greater than the pre–eclipse phase. After first contact, the Ca\textsc{i} line exhibits variations similar to the K\textsc{i} line, with an additional absorption component at about $+20$ km s\(^{-1}\) from the line rest wavelength before mid–eclipse and a blue–shifted additional absorption component developing at about 20 km s\(^{-1}\) after mid–eclipse.

---

\(^5\)The line returned to its pre–eclipse profile by our observation 2012–12–09.
We fit the pre–eclipse Ca i line with a Gaussian function and adopted the HWHM of the Gaussian (36 km s\(^{-1}\)) as the line core. The Gaussian centroid was displaced from rest by 0.08 nm (24 km s\(^{-1}\)), but the calculated radial velocity of the star was only 8 km s\(^{-1}\) for this epoch. We confirmed the Gaussian HWHM using data for two later epochs (2008–12–16, 2008–02–13) when the Gaussian centroid and stellar radial velocity were more closely aligned. We defined the wings as follows: the blue wing (−125 km s\(^{-1}\) to −36 km s\(^{-1}\)) and the red wing (36 km s\(^{-1}\) to 125 km s\(^{-1}\)). Regions outside of these defined areas consistently mapped to (0,0) in the QU–plots. These definitions are maintained throughout the following analysis.

The line appeared asymmetric in the pre–eclipse epoch (Figure 2.8) with a red absorption component extending beyond the line core, at about 50 km s\(^{-1}\). A large (c. 1%) polarization peak was nearly centered on the star and a smaller (0.4%) linear polarization peak was associated with the red–shifted component.

The presence of two peaks in \(\%p\) for this pre–eclipse epoch may be attributed to one of the following: (1) the line is optically thick at the line core (as with H–alpha), (2) more than one asymmetric region contributes to the Ca i 422.6 nm polarization, or (3) the line contains a blend of species with varying degrees of polarization. Two species, Fe i (422.743 nm, 3.3 eV, doublet) and Ti ii (422.733 nm, 1.13 eV, multiplet 33), are candidates for possible blended species corresponding to the velocity offset of c. 50 km s\(^{-1}\). The possible blended feature persisted at about the same polarization strength throughout the time series. The corresponding Fe i doublet (422.545 nm) to our candidate line exhibited no polarization in any epoch. The two other members of the Ti ii multiplet (421.818 nm and 420.592 nm) did not show polarization features. Hack (1959) identified a Ti ii line of comparable energy to
our candidate Ti II line (Ti II, 454.5 nm, 1.13 eV, multiplet 30) as a solely F star line. The feature at c. 50 km s$^{-1}$ may be a Ti II component attributable to the F star.

The QU–plot (Figure 2.9) describes two dominant position angles for the line in this pre–eclipse epoch; the excursion of ($q$, $u$; green diamonds) corresponds to the line core and the excursion ($q$; red triangles) corresponds to the red wing. The position angles corresponding to the excursions in the QU–plot differ by about 90 degrees.

The Ca i (422.6 nm) line increased in $p$ by mid–eclipse (peak polarization > 1% centered at the line rest wavelength. The polarization increased from mid–through the late eclipse and broadened on the blueward side as the blue absorption component appeared in the spectra.

The QU–plot (Figure 2.9) corresponding to mid–eclipse may be complicated by the presence of a possible blended line. The line core corresponds to ($q$, $u$; green diamonds), the excursion of ($q$, $u$; red triangles) corresponds to the red absorption wing (a possible blend) and the blue–shifted absorption corresponds to ($q$, $u$; blue squares). A similar scenario corresponds to the late eclipse QU–plot, with the notable exception that the degree of polarization has obviously increased for the line center at ($q$, $u$; green diamonds).

The $p$ decreased after 4th contact and the line returned to its pre–eclipse shape. The linear polarization exhibited two peaks in $p$, one centered on the F star and the other offset from the F star velocity by about +50 km s$^{-1}$, centered on the presumed Ti II feature. The QU–plot (Figure 2.9) describes two dominant position angles for the line in post eclipse; the excursion of ($q$; green diamonds) corre–
sponds to the line core and the excursion (+%q; red triangles) corresponds to the red wing.

We examined other Ca i lines to discover if the polarization behavior of the ground state transition was consistent with other energy transitions of this atomic species. Another Ca i line (rest wavelength 430.774 nm) arises from a higher energy level (1.9 eV) and exhibited similar line profile changes during eclipse, however, there were insufficient data points corresponding to $p/\sigma \geq 4$ to compare polarization changes of this line with changes observed in the ground state Ca i line. We observed no linear polarization signatures in other Ca i lines of comparable energy transition levels to the Ca i line at 430.774 nm.

The polarization behavior of this line suggests that Ca i (422.6 nm) traces polarization associated with the F star itself, as well as disk effects. Kim (2008) noted a 67–day out–of–eclipse light variation. We speculate that the F star polarization features we observed might be associated with upwelling and large–scale bright convective regions.

### 2.5.8 Circular polarization and Stokes $V$

We identified no significant Stokes $V$ (circular) polarization signal in any of the spectral lines we have described. Our preliminary assessment is that there are no significant circular polarization features in the data set. The presence of circular polarization signatures could indicate that magnetic fields are present and contribute to polarization; the lack of signal suggests that magnetic fields are not a major contributor to the polarization we observed.
2.6 Results

The presence of persistent polarization in spectral lines such as H–alpha, H–beta, and the Ca I 422.6 nm line out–of–eclipse suggests that asymmetry persists in the F star for extended periods. H–alpha polarization was identified in ESPaDOnS observations of ε Aur dated February 7 and 8, 2006 (Harrington and Kuhn, 2009), at phase 0.925, more than three years before the recent eclipse and about two years before periastron. Those observations, as well as the H–alpha observations presented here, indicated that the blue and red emission wings are not polarized, suggesting possible symmetry in the emitting region (at these shifted velocities/temperatures), or insufficient optical depth to generate detectable polarization from scattering in the region. We also observed that the H–alpha line does not saturate, unlike H–beta and others in the Balmer series. This suggests that a broad emission exists, contributing additional H–alpha photons to the line core.

We observed that H–alpha and H–beta exhibited different position angles in pre–eclipse. The H–beta absorption may indicate the presence of equatorially aligned hydrogen gas—the optically thick component scattering at 90 degrees perpendicular to the optically thin component. The H–alpha polarization position angles may include a component from interstellar polarization, or they may indicate a more complex distribution of hydrogen gas at those energies. Chadima et al. (2011) demonstrated that the atmosphere of the disk starts to be projected against the F star as early as three years before the beginning of the photometric eclipse; our observations seem to corroborate their findings.

H–alpha and H–beta showed similar mid– and late eclipse behavior in qu–space. The line cores and wings seem to agree about the range of angles involved, suggest-
ing that the dominant features arise from the same orientation in the sky (gaseous material above and below the disk). An offset of 90 degrees between line core and absorption wings is consistent with the effect opacity may have on scattering.

The polarization behavior of the K i (769.9 nm) line confirmed that this line has no F star component; the line may be considered a bellwether for low excitation lines affected by the disk during eclipse. Limb polarization cannot be the sole contributor to polarization signatures during eclipse (for example, Kemp et al. (1986)) because this line cannot have a limb polarization component. The disk exhibited significantly stronger polarization features in late eclipse than in any other eclipse epoch. Many observers have noted the asymmetry in the line (for example, Leadbeater et al. (2012)). The increase in polarization may indicate that the density of scattering material increased in late eclipse. Pearson and Stencil (2012) note the “dusk” face of the disk may rotate into the line–of–sight during late eclipse epochs. The warmed, presumably sublimated, material could contribute to the increased resonant scattering in the line. The position angles of scattering in late eclipse deviate from strict equatorial or polar alignment; modeling is required to replicate the late–eclipse Stokes $%q$ and $%u$ behavior.

The pre–eclipse polarization features of the Ca i (422.6 nm) line showed contributions from the F star as well as from the eclipse. The increase in polarization in late eclipse is consistent with the K i line behavior and may also suggest an increase in the density of scattering material.

The spectral and linear polarization features presented here are a sample of the features present in the data set. Only a few epochs have been presented for brevity.
We found significant changes to linear polarization in lines such as H–alpha, H–beta, Ca I (422.6 nm), and K I (796.6 nm) presented here.

2.7 Conclusions and next steps

The analysis present here is a work in progress and is not a final word. There are many spectral features whose linear polarization characteristics remain to be described. We are optimistic about the potential in these data to help characterize polarization features that may be attributed to the F star itself, as well as the polarization that arises from the eclipsing disk. Our next steps in a subsequent paper will include identification and classification of spectral features that exhibit polarization, an analysis of the position angle of linear polarization features (to fully describe the linear polarization vector), and an analysis of scattering behavior when the F star is not uniformly eclipsed.

2.8 Afterword

This paper was published in the ε Aurigae Special Edition of the Journal of the American Association of Variable Star Observers commemorating the 2009–2011 eclipse (Geise et al., 2012). We observed ε Aurigae after this paper was submitted for publication (on 2012–11–25, 2012–11–26, 2012–11–27, 2012–11–28, 2012–11–30, 2012–12–02, 2012–12–02, 2012–12–06, 2012–12–07, and 2012–12–09). The 2012–12–09 data were included in subsequent analysis (Chapters 5). The remaining data were omitted from this thesis for brevity but will be included in a subsequent publication.

In this thesis, Chapter 4 describes significant (\(> 4\sigma\)) linear polarization largely produced by atomic transitions of Fe II and Ti II observed in 11 ESPaDOnS out-of-eclipse spectra. Low position angles (near 0°) suggest that an equatorial density enhancement in the outer stellar atmosphere may contribute to the observed linear
polarization. Chapter 5 describes more than 70 lines which show significant linear polarization and gas rotation signatures during eclipse. The imprint of gas rotation is found in early eclipse in H\textalpha; most lines show the effect after mid–eclipse. These works are in preparation for publication.
<table>
<thead>
<tr>
<th>Comment</th>
<th>Gregorian</th>
<th>RJD</th>
<th>Phase</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2006–01–07</td>
<td>3774.93</td>
<td>0.926</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2008–08–25</td>
<td>4704.04</td>
<td>0.019</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2008–10–18</td>
<td>4757.92</td>
<td>0.025</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2008–12–07</td>
<td>4807.82</td>
<td>0.030</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2008–12–08</td>
<td>4808.83</td>
<td>0.030</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2008–12–09</td>
<td>4809.83</td>
<td>0.030</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2008–12–10</td>
<td>4810.83</td>
<td>0.030</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2008–12–16</td>
<td>4817.05</td>
<td>0.031</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2009–02–13</td>
<td>4875.71</td>
<td>0.036</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2009–02–14</td>
<td>4876.70</td>
<td>0.037</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2009–02–17</td>
<td>4879.85</td>
<td>0.037</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2009–05–04</td>
<td>4955.72</td>
<td>0.045</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1st contact</td>
<td>2009–08–22</td>
<td>5060.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2009–09–04</td>
<td>5079.05</td>
<td>0.057</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2009–09–05</td>
<td>5080.07</td>
<td>0.057</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2009–09–08</td>
<td>5083.15</td>
<td>0.057</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2009–09–11</td>
<td>5086.11</td>
<td>0.058</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2009–09–25</td>
<td>5100.05</td>
<td>0.059</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2009–09–26</td>
<td>5101.02</td>
<td>0.059</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2009–09–29</td>
<td>5104.03</td>
<td>0.060</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2009–10–02</td>
<td>5107.02</td>
<td>0.060</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2009–10–07</td>
<td>5112.01</td>
<td>0.060</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2009–10–10</td>
<td>5115.16</td>
<td>0.061</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2009–11–29</td>
<td>5165.11</td>
<td>0.066</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2009–12–02</td>
<td>5168.00</td>
<td>0.066</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2009–12–04</td>
<td>5169.80</td>
<td>0.066</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2009–12–07</td>
<td>5173.14</td>
<td>0.067</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2009–12–08</td>
<td>5174.14</td>
<td>0.067</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2010–01–02</td>
<td>5198.77</td>
<td>0.069</td>
<td></td>
</tr>
<tr>
<td>2nd contact</td>
<td>2010–01–02</td>
<td>5200.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2010–01–26</td>
<td>5222.71</td>
<td>0.072</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2010–01–28</td>
<td>5224.70</td>
<td>0.072</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2010–03–08</td>
<td>5263.72</td>
<td>0.076</td>
<td></td>
</tr>
<tr>
<td>mid–eclipse</td>
<td>2010–07–06</td>
<td>5390.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2010–07–23</td>
<td>5401.12</td>
<td>0.090</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2010–08–01d</td>
<td>5410.13</td>
<td>0.090</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2010–08–05d</td>
<td>5414.11</td>
<td>0.091</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2010–10–16</td>
<td>5485.91</td>
<td>0.098</td>
<td></td>
</tr>
</tbody>
</table>

Continued on Next Page...
<table>
<thead>
<tr>
<th>Comment</th>
<th>Gregorian</th>
<th>RJD&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Phase&lt;sup&gt;c&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010–10–18</td>
<td>5487.90</td>
<td>0.098</td>
<td></td>
</tr>
<tr>
<td>2010–10–19</td>
<td>5488.99</td>
<td>0.098</td>
<td></td>
</tr>
<tr>
<td>2010–10–21</td>
<td>5490.93</td>
<td>0.099</td>
<td></td>
</tr>
<tr>
<td>2010–11–15</td>
<td>5516.02</td>
<td>0.101</td>
<td></td>
</tr>
<tr>
<td>2010–11–16</td>
<td>5517.14</td>
<td>0.101</td>
<td></td>
</tr>
<tr>
<td>2010–11–17</td>
<td>5517.96</td>
<td>0.101</td>
<td></td>
</tr>
<tr>
<td>2010–11–22&lt;sup&gt;d&lt;/sup&gt;</td>
<td>5522.89</td>
<td>0.102</td>
<td></td>
</tr>
<tr>
<td>2010–11–24&lt;sup&gt;d&lt;/sup&gt;</td>
<td>5524.99</td>
<td>0.102</td>
<td></td>
</tr>
<tr>
<td>2010–12–19</td>
<td>5549.74</td>
<td>0.105</td>
<td></td>
</tr>
<tr>
<td>3&lt;sup&gt;rd&lt;/sup&gt; contact</td>
<td>2011–03–18</td>
<td>5620.00</td>
<td></td>
</tr>
<tr>
<td>4&lt;sup&gt;th&lt;/sup&gt; contact</td>
<td>2011–05–21</td>
<td>5720.00</td>
<td></td>
</tr>
<tr>
<td>2011–08–17</td>
<td>5791.13</td>
<td>0.129</td>
<td></td>
</tr>
<tr>
<td>2011–11–01</td>
<td>5867.13</td>
<td>0.137</td>
<td></td>
</tr>
<tr>
<td>2011–11–15&lt;sup&gt;d&lt;/sup&gt;</td>
<td>5880.99</td>
<td>0.138</td>
<td></td>
</tr>
<tr>
<td>2011–11–16&lt;sup&gt;d&lt;/sup&gt;</td>
<td>5882.16</td>
<td>0.138</td>
<td></td>
</tr>
<tr>
<td>2012–01–06</td>
<td>5933.00</td>
<td>0.143</td>
<td></td>
</tr>
<tr>
<td>2012–01–17</td>
<td>5943.78</td>
<td>0.144</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup>RJD for eclipse taken from Stencel et al. (2011)

<sup>b</sup>Julian Date – 2450000

<sup>c</sup>Time of periastron and period from Stefanik et al. (2010) 2434723+9896.0E

Figure 2.1: Time series of H–alpha (656.280 nm) line and %p profiles for pre–, mid–, and late–eclipse epochs. Velocity is centered on the line rest wavelength. The F star radial velocity is indicated by a star symbol. Note the star is slightly red-shifted pre–eclipse and blue–shifted late eclipse. Polarization data are epoch– (see text) and wavelength–binned (bin size 0.015 nm). Average errors in %p are shown.
Figure 2.2: QU–plots of H–alpha (656.280 nm) for pre–, mid–, late, and post–
eclipse epoch and wavelength binned data. The first date of each binned epoch is
given. Average error bars are shown. Note the QU–plot is nearly linear in pre–
eclipse. The prominent excursion (−%q, −%u; green diamonds) corresponds to the
line core (±25 km s\(^{-1}\)). Absorption wing contributions appear in mid– and late–
eclipse. The blue wing corresponds to (+%q, +%u; blue squares) and the red wing
corresponds to (+%q,−%u; red triangles) in mid–eclipse. By late eclipse, the red
wing polarization has largely disappeared (near 0,0) and the large +%q excursion
is blue wing polarization. The line core polarization is (+%u, %q; green diamonds)
in post eclipse. These data have been rotated into the stellar frame (see text for
description).
Figure 2.3: Position angle calculated for (%q, %u) pairs for the H–alpha line in mid–eclipse. The data are rotated to the stellar frame and unbinned. Notice that the linear polarization position angle appears randomly scattered outside of the line, which is expected. The position angles that correspond to the line core (+25 km s$^{-1}$ from rest wavelength) are plotted in green; position angles corresponding to the blue–shifted absorption wing ($-125$ km s$^{-1}$ to $-25$ km s$^{-1}$) are plotted as blue star–shapes; and position angles corresponding to the red–shifted absorption wing (+25 km s$^{-1}$ to +125 km s$^{-1}$) are plotted as red star–shapes. Position angles only range from 0° to 180° because of the nature of the Stokes parameters; a position angle of 180° is consistent with 0°. Notice the line core polarization is offset by about 90° from the wings. This may be an opacity effect. Compare these data to the mid–eclipse QU–plot (Figure 2.2) and mid-eclipse line profile (Figure 2.1).
Figure 2.4: Time series of H–beta (486.135 nm) line and %p profiles for pre–, mid–, and late–eclipse epochs. Velocity is centered on the line rest wavelength. The F star radial velocity is indicated by a star symbol. Polarization data are epoch– (see text) and wavelength binned (bin size 0.015 nm). Average errors in %p are shown. The line is clearly saturated in late eclipse, falling to just 1.6% intensity at the deepest point and, although S/N is nearly 200 here, the ratio p/σ is only 1.2; therefore %p = 0. The ratio p/σ ranges from 3 to 11 for %p > 0.4 outside the saturated region.
Figure 2.5: QU–plots of H–beta (486.135 nm) for pre–, mid–, late–, and post–eclipse epoch– and wavelength–binned data. The first date of each binned epoch is given. Average error bars are shown. Absorption wing contributions appear in mid– and late–eclipse. The blue wing corresponds to (+%q, +%u; blue squares) and the red wing corresponds to (+%q, −%u; red triangles) in mid–eclipse. Line core is −%q (green diamonds). By late eclipse, the red wing polarization has disappeared (centered on 0,0) and the large +%q excursion is blue wing polarization (blue squares). The line core polarization is +%u in post eclipse. These data have been rotated into the stellar frame (see text for description).
Figure 2.6: Time series of K I (769.896 nm) line and %p profiles for pre–, mid–, and late–eclipse epochs. Velocity is centered on rest wavelength. Polarization data are epoch– (see text) and wavelength–binned (bin size 0.015 nm). The out–of–eclipse line is thought to have an interstellar origin. Note the star is red–shifted pre–eclipse, but the line core is not red–shifted and the line exhibits no polarization features. Disk contributions to the line in late eclipse are blue–shifted and exhibit polarization features.
Figure 2.7: QU–plots of K i (769.896 nm) for pre–, mid–, late–, and post–eclipse epoch– and wavelength–binned data. The first date of each binned epoch is given. Average error bars are given. The out–of–eclipse line is thought to have an interstellar origin (for example, Welty and Hobbs (2001)). Note there are no polarization features pre–eclipse or post eclipse. Disk contributions appear after mid–eclipse. The (−%q, +%u; blue squares) excursion corresponds to the blue–shifted absorption wing. These data have been rotated into the stellar frame (see text for description).
Figure 2.8: Time series of Ca i (422.673 nm) line and \%p for pre–, mid–, and late–eclipse epochs. Velocity is centered on the line rest wavelength. This line corresponds to a ground state transition. Note the dramatic increase in linear polarization in later epochs. The data are epoch– (see text) and wavelength–binned (bin size 0.015 nm). Average errors in \%p are shown.
Figure 2.9: QU–plots of Ca i (422.673 nm) for pre–, mid–, late–, and post–eclipse epoch– and wavelength–binned data. The first date of each binned epoch is given. Average error bars are shown. Absorption wing contributions appear in mid– and late–eclipse. The QU–loop (green diamonds) largely corresponds to line core, with small red wing contributions in +%q in mid–eclipse (red triangles). By late–eclipse, the QU–loop has grown with small −%q contributions from the blue wing (blue squares) and +%q contributions from the red wing. The “flattened” QU–loop corresponds to line core (green diamonds) in post eclipse. These data have been rotated into the stellar frame (see text for description).
Chapter 3

Probing disk inhomogeneities using spectropolarimetry
in the extreme binary epsilon Aurigae

3.1 Summary

We obtained 50+ epochs of high dispersion optical spectropolarimetric data from the ESPaDOnS instrument at the Canada–France–Hawaii Telescope before, during, and after the most recent eclipse (2009–2011). We found numerous 3-sigma (or greater) linear polarization features in the spectra and associated these with atomic absorption features also present in the spectra. We observe dramatic changes to polarization and position angles with time during eclipse, particularly around 3\textsuperscript{rd} contact. The increased polarization could be due to a localized increased number of scatterers.

3.2 Introduction

\(\varepsilon\) Aurigae is a single line spectroscopic binary system comprised of a variable F0 supergiant star (the visible star in the system) and a dusty disk surrounding a presumed B star (Fig. 3.1). The F0 star is sometimes characterized as an irregularly variable star or a non-radial pulsator. The system eclipses once every 27 years for a duration of two years, among the longest periods of totality for known eclipsing systems. Many characteristics of \(\varepsilon\) Aurigae are still poorly defined, including the mass of each object, spectral type of the binary companion, origin of the disk, and evolutionary status of the system, largely because the distance is uncertain. An ultraviolet excess in the spectral energy distribution suggests the second object is a
B5 star (Hoard et al., 2010). We have made use of spectropolarimetry in order to improve knowledge of the components in this system.

3.3 Observations & Methods

More than 50 high resolution spectra were obtained from the Canadian Data Center (CADC) archives for the Echelle SpectroPolarimetric Device for the Observation of Stars (ESPaDOnS) instrument at the Canada-France-Hawaii telescope (CFHT). ESPaDOnS is a cross-dispersed echelle spectropolarimeter designed to obtain a complete optical spectrum (370 nm to 1000 nm) in a single exposure, with a resolving power of about 65,000 and signal-to-noise greater than 500 (Donati, 2003). Observations were taken by Nadine Manset as the principal investigator, before, during and after the most recent eclipse.

Linear polarization and position angle were computed from Stokes $Q$ and $U$ using the formulation described in Bagnulo et al. (2009). We were careful to reverse the sign of Stokes $U$ as noted in the ESPaDOnS FITS header. Interstellar polarization was removed by Libre–ESpRIT, the data reduction pipeline for ESPaDOnS (Donati et al., 1997). Polarization data were binned (bin size 0.008 nm) and bias–corrected. Spectra were corrected for F0 star stellar motion using the orbital solution from Stefanik et al. (2010). Polarization data were rotated to align instrument north with the rotation axis of the system as described by Kloppenborg et al. (2010).

We calculated the normalized flux equivalent width (EW) by integrating across the line. We corrected for small variations in the line normalization by subtracting an equivalent width, calculated from the featureless continuum adjacent to the line, and measured using the same wavelength span as the EW. We calculated integrated polarized flux EW by integrating $P = \sqrt{Q^2 + U^2}$ across the line using the same
wavelength span as the flux EW. We corrected for positive bias in the polarized flux by subtracting an integrated polarized flux EW also calculated using adjacent featureless continuum.

### 3.4 Results & Conclusions

Polarization increases dramatically during eclipse in species such as Fe I, Fe II, Ti II, Sc II and others (Geise et al., 2012). Polarization peaked around 3rd contact for many species consistent with the observed increase in absorption. We observe persistent linear polarization in several lines, including Hα, even outside of eclipse.

*Fe II (4657 Å and 4924 Å).* The variability of the F0 star is evident in the photospheric line Fe II (4657 Å; $E_i = 2.89$ eV, $E_k = 5.55$ eV, $A_{ki} = 1.4 \times 10^4$ s$^{-1}$). This line does not exhibit increased absorption during eclipse (Strassmeier et al., 2014), but does exhibit out-of-eclipse linear polarization (Figs. 3.2 & 3.4). The Fe II (4924 Å; $E_i = 2.89$ eV, $E_k = 5.40$ eV, $A_{ki} = 4.3 \times 10^6$ s$^{-1}$) line exhibits additional disk absorption, first red-shifted in early eclipse and then blue-shifted in late eclipse (Fig. 3.6). The EW appears to peak after mid-eclipse and an increase in polarized flux is also evident (Fig. 3.8). Although these lines have similar transition energies and arise from the same lower level, the longer wavelength line (4924 Å) is the stronger line. The Fe II (4731 Å; $E_i = 2.89$ eV, $E_k = 5.51$ eV, $A_{ki} = 2.8 \times 10^4$ s$^{-1}$) line, another in the multiplet, shows no additional disk absorption and exhibits similar polarization behavior as the weaker Fe II (4657 Å) line.

*K I (7699 Å).* Lambert and Sawyer (1986) observed that the equivalent widths of K I 7665 Å and 7699 Å appeared bi-lobed during the prior eclipse (1982–1984); the EW attained a maximum value just following the onset of totality (2nd contact) and just prior to the end of totality (3rd contact). This line behavior was
repeated during the most recent eclipse (Leadbeater et al., 2012; Strassmeier et al., 2014). The absorption line consisted primarily of an interstellar feature outside of eclipse. Our calculated equivalent widths closely resemble those by these observers (Fig. 3.10). Significant linear polarization (>3 sigma) is not observed in K I (7699 Å) in our spectra until Nov 2010, more than 100 days after mid–eclipse, even though red–shifted absorption attributed to the disk is observed in the line near 1st contact, in Sept 2009. The linear polarization returns to near zero by August 2011, our first observation after 3rd contact.

\[ H\alpha (6563 \text{ Å}) \] Mauclaire et al. (2012) found the equivalent width of the Hα line to be anti–correlated with the observed V band magnitude during eclipse. The EW increased as the V magnitude decreased with the onset of eclipse and decreased as the system brightened after 3rd contact. Our eclipse coverage has a 9–month gap beginning about 2 months before 3rd contact and ending just prior to 4th contact, but our EW data reflect similar variations with time as those of other observers. Compare the Hα EW to the bi–lobed EW observed in K I (7699 Å). The linear polarization generally increases with increasing absorption, especially in the line wings, but we observe epochs of low integrated polarized flux during eclipse (Fig. 3.12).

Polarization associated with absorption lines (both line absorption, %p, and polarized flux, P) reveal that gas is not distributed evenly in the disk. For example, the leading edge of the disk is observed to be less polarized than the trailing edge of the disk for many gas species, such as K I (7699 Å), presented here. Some lines exhibit greater polarization for a brief time (∼2 months) in spectra taken before 3rd contact, similar to the continuum polarization (Cole, 2012), possibly due to a localized increase in the number of scatterers. The behavior of Hα EW and polarized flux differs from K I (7699 Å). The Hα EW does not appear bi–lobed and no large
increase in polarized flux is observed in Hα near 3rd contact. This suggests that the hydrogen gas may have a more extended distribution in the system. The polarized flux variability we observe during eclipse in atomic transitions such as K I may indicate the presence of sub-structure in the distribution of gas associated with the disk. We also find polarization signatures attributable to disk rotation (Geise et al. 2015, in prep., see Chapter 5).

3.5 Afterword

This work was accepted for publication in March, 2015: Kathleen Geise & Robert Stencel, 2015, Proceedings of the IAU Symposium No. 305. The equivalent width and polarized flux equivalent width plots presented in this thesis document are epoch-binned data. The plots originally submitted for publication were updated to reduce noise and improve readability. See Chapter 5, Section 5.3.1 for details about the binning used in the updated plots presented here and Section 5.6 for a discussion of the observed polarization near 3rd contact.
Figure 3.1: Composite image of $\varepsilon$ Aurigae. The disk of $\varepsilon$ Aurigae revealed in a composite series of interferometric images taken during the 2009–2011 eclipse at 1.1 $\mu$m wavelength. Image courtesy of B. Kloppenborg & R. Stencel.
Figure 3.2: Fe ii (4657 Å) line profiles and polarization (%p) spectra at pre-eclipse (2008–10–18), mid–eclipse (2010–08–01) and late eclipse (2010–12–19) epochs. Data are binned (bin size 0.008 nm), centered on the line rest wavelength and corrected for stellar motion using the ephemeris from Stefanik et al. (2010).
Figure 3.3: Fe II (4657 Å) QU–plot at pre–eclipse (2008–10–18), mid–eclipse (2010–08–01), late eclipse (2010–12–19) and post–eclipse (2012–01–17) epochs. Data are epoch–binned (bin size 0.008 nm) and are rotated into the stellar frame. The blue wing (blue square), red wing (red triangle), and line core (±25 km s$^{-1}$, green diamond) polarization are shown. Loops in the QU–plot arise from scattering by velocity–shifted material observed primarily in Stokes $U$ in the line wings. Average uncertainty in %q and %u indicated by crosses.
Figure 3.4: Fe ii (4657 Å) equivalent width (EW) calculated from ESPaDOnS spectra by integrating across the line between 4656.0 Å and 4658.3 Å, normalized to adjacent off-line continuum. The line is evidently variable, but no large increase in EW was observed during eclipse. Mid-eclipse is marked by the dashed line. Eclipse epochs 1st contact (leftmost line), 2nd contact, 3rd contact and 4th contact are marked by short vertical lines. Uncertainties smaller than the plotting symbols.
Figure 3.5: Fe ii (4657 Å) polarized flux EW calculated from ESPaDOnS spectra by integrating across the line between 4656.0 Å and 4658.3 Å, normalized to adjacent off-line continuum. Mid-eclipse is marked by the dashed line. Eclipse epochs 1st contact (leftmost line), 2nd contact, 3rd contact and 4th contact are marked by short vertical lines. Scattered light may contribute to the increase in polarized flux and percent polarization (\%p) observed during some eclipse epochs.
Figure 3.6: Fe II (4924 Å) line profiles and polarization (%p) at pre-eclipse (2008–10–18), mid–eclipse (2010–08–01) and late eclipse (2010–12–19) epochs. Data are binned (bin size 0.008 nm), centered on the line rest wavelength and corrected for stellar motion using the ephemeris from Stefanik et al. (2010). Symbols as in Fig. 3.2.
Figure 3.7: Fe II (4924 Å) QU–plot at pre-eclipse (2008–10–18), mid–eclipse (2010–08–01), late eclipse (2010–12–19) and post–eclipse (2012–01–17) epochs. Data are epoch–binned (bin size 0.008 nm) and are rotated into the stellar frame. The blue wing (blue square), red wing (red triangle), and line core (±25 km s$^{-1}$, green diamond) polarization are shown.
Figure 3.8: Fe II (4924 Å) equivalent width calculated from ESPaDOnS spectra by integrating across the between 4922.0 Å and 4926.5 Å, normalized to adjacent off-line continuum (left). The line is evidently variable, but no large increase in EW was observed during eclipse. Mid–eclipse is marked by the dashed line. Eclipse epochs 1st contact (leftmost line), 2nd contact, 3rd contact and 4th contact are marked by short vertical lines. Compare this line to Fe II 4657 Å (Fig. 3.4).
Figure 3.9: Fe II (4924 Å) polarized flux EW calculated from ESPaDOnS spectra by integrating across the between 4922.0 Å and 4926.5 Å, normalized to adjacent off-line continuum. Mid-eclipse is marked by the dashed line. Eclipse epochs 1\textsuperscript{st} contact (leftmost line), 2\textsuperscript{nd} contact, 3\textsuperscript{rd} contact and 4\textsuperscript{th} contact are marked by short vertical lines. Note the increase in polarized flux after mid-eclipse, near 3\textsuperscript{rd} contact. Compare this line to Fe II 4657 Å (Fig. 3.4).
Figure 3.10: K i (7699 Å) equivalent width (black circle) compared to results of Strassmeier et al. (2014) (red asterisk). An interstellar component has been removed from the equivalent width. Mid–eclipse is marked by a vertical dashed line; 1st, 2nd, 3rd and 4th contact are denoted by solid lines. Note the variable, presumed F0 star, absorption observed in the line out–of–eclipse.
Figure 3.11: K i (7699 ˚A) polarized flux EW calculated from ESPaDOnS spectra by integrating across the line, normalized by offline polarized flux. Mid–eclipse is marked by a vertical dashed line; 1st, 2nd, 3rd and 4th contact are denoted by solid lines. Note the increase in polarized flux after mid-eclipse, near 3rd contact.
Figure 3.12: H\textsc{i} (6563 Å, H\(\alpha\)) equivalent width calculated from ESPaDOnS spectra by integrating between 6550 Å and 6577 Å, normalized to adjacent off–line continuum; EW includes absorption and emission. Mid–eclipse is marked by a vertical dashed line; 1\textsuperscript{st}, 2\textsuperscript{nd}, 3\textsuperscript{rd} and 4\textsuperscript{th} contact are denoted by solid lines. The large velocity–shifted absorption contributed by the disk is demonstrated by the increase in EW by mid–eclipse. Compare these observations to the largely–disk absorption of the K\textsc{i} (7699 Å) line.
Figure 3.13: H\textsc{i} (6563 Å, H\(\alpha\)) polarized flux EW calculated by integrating between 6550 Å and 6577 Å, normalized by offline polarized flux EW. Mid-eclipse is marked by a vertical dashed line; 1\textsuperscript{st}, 2\textsuperscript{nd}, 3\textsuperscript{rd} and 4\textsuperscript{th} contact are denoted by solid lines. Percent polarization (\(\%p\)) increased during eclipse as the line deepened with additional disk absorption. Polarized flux appeared to increase after 1\textsuperscript{st} contact, but some eclipse epochs exhibited low polarized flux (e.g. near RJD 5200). No large increase in polarized flux was observed near 3\textsuperscript{rd} contact. Compare these observations to K\textsc{i} (7699 Å).
Chapter 4

An analysis of the most polarized atomic lines in ESPaDOnS out–of–eclipse observations of ε Aurigae

4.1 Summary

We evaluated spectral features and linear polarization in out–of–eclipse observations in order to characterize line polarization observed in the system. We were motivated to understand the out–of–eclipse behavior in order to remove the signal from our eclipse observations. The ESPaDOnS spectra presented here spanned periastron and sampled the time leading up to the most recent eclipse (2009–2011). We identified significant (≥ 4σ) linear polarization peaks and associated them with spectral absorption features. We identified the scattering geometry by analyzing the dominant polarization position angles. We find the line core absorption most closely corresponds to the rest wavelength of each atomic transition when spectral features are adjusted for F0 star radial velocities using a recent ephemeris. Polarization is persistent in out–of–eclipse observations and appears strongest in the core of each associated spectral line. The F0 star line polarization is variable in time and strength. We do not detect polarization associated with the disk around the unseen star; the polarization we detect is seen around the primary. The polarization likely arises from an equatorial density enhancement in the gas in the outer layers of the F0 star.
4.2 Introduction

The $\varepsilon$ Aurigae system is a known irregularly variable eclipsing system with typical non-periodic $V$ band brightness variations of $\sim$0.1 mag and an eclipse variation of 0.8 mag (SIMBAD catalog $V$ band magnitude 2.99\(^1\)). There is a close linear correlation between brightness and color: the star is bluest (hottest) when brightest (Gyldenkerne, 1970; Carroll et al., 1991). Epsilon Aurigae was classified as an $\alpha$ Cygni type variable star using an automated classification of the Hipparcos periodic variable stars into 26 types using a random forest method (Dubath et al., 2011). Variables of the $\alpha$ Cygni type are characterized as non-radially pulsating supergiants of Bep-Aep Ia spectral types\(^2\). The system has been observed by modern instruments in wavebands from the far–UV to the far–IR, and by visual observers for more than 100 years. For a summary of recent observations see Stencel et al. (2011); Stencel (2013) and references within. Important dates for the recent eclipse (e.g. mid–eclipse 2010 July 22) are given in Stencel (2012).

We adopt orbital elements given by Stefanik et al. (2010) in our analysis: phase 0.0 corresponds to periastron and mid–eclipse occurs at phase $\sim$0.09 (JD 2,455,413.8 $\pm$ 4.8, 2010 August 5). In this reckoning, the photometric eclipse begins near phase 0.056 and ends near phase 0.130, apastron is at phase 0.5 and secondary eclipse (never observed at visible wavelengths) occurs near phase $\sim$0.6. The mass function is given by $f(M_\odot) = 2.51 \pm 0.12$ (Stefanik et al., 2010).

4.2.1 F0 star

Spectral absorption features attributable to the disk are not observed in visible spectra except during eclipse. For example, a transient He I (10830 Å) disk absorp-
tion increase has been observed in the infrared (Stencel et al., 2011) and molecular CO absorption lines are also intermittent (Stencel et al., 2015).

The F0 star spectral features have been observed to vary on timescales of one or two months even during eclipse. The F0 star features in the visible spectra are seen in absorption, except for H\(\alpha\) which has a persistent emission component. There is also evidence for underlying emission in other hydrogen lines of F0 star origin (Castelli, 1978). In addition, the H\(\alpha\) line (absorption and emission) is known to be highly variable out–of–eclipse (e.g. Cha et al., 1994; Schanne, 2007). H\(\alpha\) emission is unusual in F supergiant stars and may arise in a ring of material or a nebulosity encircling the star, or in an expanding circumbinary envelope (e.g Struve, 1956; Kemp et al., 1986; Cha et al., 1994). Saito et al. (1987) modeled an H\(\alpha\) emitting region 1.15 times the photospheric diameter of the primary along the orbital plane and 0.2 times along the z–axis to best fit their observations. Chadima et al. (2011) found that the H\(\alpha\) emission followed the F0 star orbit. Mourard et al. (2012) suggested that although the interferometric visibility in H\(\alpha\) followed the F0 star orbital motion, the lower amplitude of the H\(\alpha\) RV curve they derived from visible spectra compared to Si II and Fe II lines might indicate that the optical center of gravity of the H\(\alpha\) emission could be closer to the barycenter of the system than the mass center of the F0 star. However, Ferluga and Mangiacapra (1991) found the radial velocities of hydrogen to have a greater amplitude than metal lines in spectra taken during the previous (1982–1984) eclipse.

Several observers have commented that the F0 star envelope is extended and that the conditions for local thermodynamic equilibrium are likely not met, especially in the outer regions of the photosphere (e.g. Hack, 1959; Castelli, 1978; Chadima et al., 2011). Fitting model atmospheres to the F0 star spectrum has been complicated
by this issue. The outer atmosphere has been found to be tenuous (surface gravity, log $g \sim 1.0$). In addition, radial velocity (RV) and equivalent width (EW) measurements of spectral features are made difficult by the short–term variations in spectral lines both in– and out–of–eclipse.

Sadakane et al. (2010) undertook an abundance analysis of the primary star in epsilon Aurigae and noted that the line profiles of metallic absorption lines often showed skewed, or even double-bottomed, shapes during the course of their observations. These authors further commented that complex variations in the profiles of metallic lines most probably reflect large–scale motions in the outer layer of the stellar atmosphere and that using static model atmospheres for interpreting the metallic lines in this star might be inadequate.

Hack (1959) completed a curve of growth analysis using spectra from two out–of–eclipse epochs, one with sharp lines and one with broadened but shallower lines. She found about 20% more absorption on average in broad line profiles compared to corresponding sharp line profiles. She also found that macroturbulence increased with the increased absorption. Hack attributed the variation in the line contours primarily to variations in macroturbulence.

The dynamical motion of the stellar atmosphere was described by Castelli (1978). Using spectroscopic analysis, Castelli deduced a large scale motion of about 23 km s$^{-1}$ in the deepest layers of the F0 star which decreased toward the upper layers. She described the photosphere as extended in a non–LTE expanding envelope. In this scenario, instabilities in the interior of the star drive outward motion and infalling gravitationally–bound material collides with outwardly moving material to create a temperature inversion, or chromosphere, which accounts for the observed
hydrogen emission. The layers of the stellar atmosphere do not tend to move in unison; a contraction should be observable in the deepest layers when the upper layers are still in expansion, for example.

Finally, evidence for an F0 star wind has been observed in additional blue–shifted absorption in the Ca II K (393.4 nm) line (Castelli, 1978; Griffin and Stencel, 2013) and in the far–UV spectrum Ake (2006). Struve (1956) found evidence for an expanding atmosphere at very high elevations in the violet edges of strong low level lines such as Ti II (375.9 nm, 376.1 nm) and from additional blue–shifted absorption observed in neutral sodium. Backman et al. (1985) observed H I Brα (n = 5 – 4, λ= 4.052 µm) and Brγ (n = 7 – 4, λ= 2.166 µm) emission components attributed to the F0 star that were not eclipsed by the secondary. Backman et al. determined that the velocity structure of the H I emission components (Hα, Brα, Brγ) indicated that the emission could originate in a wind or flow. Strassmeier et al. (2014) also attributed Hα emission to an F0 star wind. These authors also deduced that the rotation axis of the F0 supergiant is perpendicular, or nearly so, to the orbital plane.

Linear polarization may arise from light scattering on material along the line–of–sight in the presence of some anisotropy. The scatterer may be dust grains (large or small in size), electrons, atoms or molecules and the polarization may be modulated in the presence of magnetic fields. The F0 star is variable on short timescales both in brightness and polarization (see below). A V band light curve of the most recent eclipse (illustrating brightness variability) and a schematic of the system may be found in Stencel (2012) (Figs. 5 & 6). The stellar atmosphere is very dynamic, evidenced by the highly variable medium and strong spectral lines. The atmosphere is in large–scale turbulent motion and the outer envelope is very tenuous. Evidence for an expanding envelope or wind has been described in the literature as well as
evidence for the presence of an ionized equatorial ring. These features of the atmosphere create an opportunity for an anisotropic distribution of material to form around the star. This study considers linear polarization that likely arises due to an anisotropic distribution of atoms in the F0 star envelope.

The present study is organized as follows: observations and reductions are described in section 4.3; results of spectral analysis in section 4.4; results of spectropolarimetric analysis in section 4.5; and discussion and conclusions in section 4.6.

4.3 Observations and reductions

4.3.1 Spectra and spectropolarimetry

High-resolution échelle spectropolarimetric data were obtained with the 3.6 m Canada–France–Hawaii optical/infrared telescope (CFHT) using the Échelle SpectroPolarimetric Device for the Observation of Stars (ESPaDOnS). More than 50 spectra of ε Aurigae were obtained over a 4 year period from pre–eclipse, through the nearly 2 year eclipse cycle (1st contact, 2009 August 16) and up to about a year after eclipse (4th contact, 2011 August 26). An earlier 2006 observation of ε Aurigae is also included in this study. We present an analysis of eleven pre–eclipse observations that span nearly three years from early 2006 to early 2009 (see Table 4.1). It is important to understand the out–of–eclipse polarization in order to remove the signal from the eclipse data. Our analysis of eclipse observations is the focus of a future paper (Geise 2015, in prep.).

ESPaDOnS is a cross-dispersed échelle spectropolarimeter designed to obtain a complete optical spectrum (370 nm to 1,050 nm) in a single exposure, with a resolving power of \( \sim 65 \, 000 \) (Donati, 2003; Donati et al., 2006). All 4 Stokes parameters were taken for each observation (see Table 4.1 for a log of observations). ESPaDOnS
data are archived as FITS files, with one file for each of the 3 Stokes parameters: $Q$, $U$, $V$. Total observed intensity, $I$ (the 4th Stokes parameter), is included in each file with wavelengths in nm. We made use of the fully–reduced, normalized data from each observation. We were careful to reverse the sign of Stokes $U$ as noted in the ESPaDOnS FITS header. We checked the included null parameters to be sure there was no spurious polarization in the data.

We retrieved ESPaDOnS observations of ε Aurigae from the Canadian Astronomy Data Centre (CADC)\(^3\), Canada France Hawaii Telescope (CFHT) Science Data Archive. The data were automatically reduced with Upena, CFHTs reduction pipeline for ESPaDOnS. Upena uses Libre–ESpRIT, which is a proprietary data reduction software tool (Donati et al., 1997).

The ESPaDOnS data are noisier at shorter wavelengths (i.e. toward the blue) than longer wavelengths because the detector is less sensitive in the blue. We binned the linear polarization data with a wavelength bin of 0.008 nm using the error–weighted mean to boost signal–to–noise at shorter wavelengths and for deep absorption lines. In some cases, we combined several epochs (using the error–weighted mean) to further reduce noise using the criterion that the line profile did not change between binned epochs (typically one day apart). We chose the bin size to ensure that there were no empty bins (except for the three very small gaps in the échelle spectrum) for the entire wavelength span of the observations. See Table 4.1 for the specific epochs used in binning.

\(^3\)online http://www1.cadc-ccda.hia-iha.nrc-cnrc.gc.ca/cadc/
4.3.2 Stellar reference frame

\(\varepsilon\) Aurigae is considered a single line spectroscopic binary system and the out–of–eclipse absorption features observed in visible light are attributed to the F0 star. The motion of the F0 star has been described using historic and recent radial velocity measurements and times of eclipse (Stefanik et al., 2010; Chadima et al., 2011). We adopt the ephemeris of Stefanik et al. (2010) in this analysis.

The \(\varepsilon\) Aurigae system was imaged interferometrically by Kloppenborg et al. (2010) and the disk seen in eclipse was observed to be tilted with respect to north on the sky. Based on the imaging interferometry and as a first approximation to the dominant geometry of the system, we assume that the disk and orbital plane are co–planar and the rotation axis of the F0 star is perpendicular to the orbital plane. We assume that scattering material in the system is likely to be distributed in the orbital plane (or perpendicular to the plane, as in the case of jets). We adopted a rotation angle of 27° to align north with the axis perpendicular to the observed (inferred) orbital plane of the system. We rotated \(Q\) and \(U\) data using a rotation matrix (e.g. Bagnulo et al., 2009) before calculating linear polarization and position angles. Unless explicitly stated otherwise, all position angles in this study are calculated using data rotated into the disk/stellar reference frame.

4.3.3 Equivalent width

We employed direct integration of the observed line to calculate equivalent widths (EW) using unbinned ESPaDOnS data (Table 4.2). We compared our results with published values whenever possible. We integrated polarized flux across the line using binned ESPaDOnS data in order to compare the change to the scattered flux density over time (Table 4.3). Inherent in this analysis is the assumption that the
data are free of interstellar polarization. We analyzed changes to position angle (PA) separately (see below).

The K I (769.896 nm) line consists primarily of an interstellar absorption feature in out–of–eclipse spectra. We expected an interstellar line to remain constant on the timescale of our observations. We tested this hypothesis by removing an interstellar contribution to the K I (769.896 nm) line as follows. We calculated a normalized spectrum by dividing each of our binned spectra by the error–weighted mean of four out–of–eclipse observations that did not exhibit a variable blue–shifted line feature (see discussion, below). We used binned intensities for this analysis to correct for the minor wavelength shifts imposed by the échelle spectrometer. We then integrated these normalized interstellar–corrected out–of–eclipse spectra to determine the EW of the additional intrinsic absorption.

4.3.4 Line strength

We measured the central depth of the line from the continuum \(f_{\text{line}}\) by selecting the point of minimum flux within the range of wavelengths used to measure the equivalent width of the line. We defined a strong line as one that absorbed 40% or more of the normalized continuum flux in out–of–eclipse spectra \(f_{\text{line}} \leq 0.60\). We defined medium strength lines as absorbing 25% to 40% of the continuum \(0.75 \geq f_{\text{line}} > 0.60\). Weak lines absorbed less than 25% of the continuum \(f_{\text{line}} > 0.75\). We calculated the velocity offset in the F0 star reference frame by correcting for F0 star motion using the ephemeris of Stefanik et al. (2010). The velocity correction then placed the line rest wavelength at 0 km s\(^{-1}\) for all observations. The central depth was sometimes offset from the line rest wavelength because of the variability of the F0 star.
4.3.5 Linear polarization

The ESPaDOnS pipeline removes the continuum polarization, regardless of its origin (instrumental, interstellar or circumstellar). We confirmed this assumption by plotting largely interstellar lines such as the K I absorption feature and noting that the scatter in the QU–plane was centered on (0,0). Featureless continuum was also centered on (0,0) in the QU–plane. Any residual contribution from interstellar polarization would shift the zero position to another point on the Q,U–plane.

We calculated linear polarization, \( P \), using the ESPaDOnS Q and U Stokes parameters and the method described by Bagnulo et al. (2009), where \( P = \sqrt{Q^2 + U^2}/I \) and linear polarization is usually given as a percent, \( \%P \). This formulation yields a measure of scattered light as a percent of the total observed flux density. We calculated polarized flux using \( P = \%P \times I/100 = \sqrt{Q^2 + U^2} \). We were careful to correct Stokes U by taking the negative of the archived value as described in the FITS file header. We observed no significant (>4\( \sigma \)) Stokes V circular polarization in our ESPaDOnS data.

By definition, the parameter \( P \) is a positive definite quantity. The individual polarization values calculated will always be positive and non-zero because the individual values of Q and U will generally be non-zero. When null, Q and U scatter around zero with uncertainty described by Poisson statistics, but linear polarization, \( P \), is described by Rician statistics. We corrected for bias in \( P \) (e.g. Simmons and Stewart, 1985) and we calculated average linear polarization using average Stokes Q and U (e.g. Clarke and Stewart, 1986).

We corrected for the positive bias in the integrated polarized flux by integrating a featureless portion of the normalized continuum adjacent to the line and with the
same width in wavelength. We then subtracted this integrated, but positive, null amount from the integrated polarized flux across the line. The resulting amount (line minus continuum) represents the polarized flux of intrinsic contributions observed in the line.

We calculated the line core polarization ($\%p$) using an error–weighted average Stokes $Q$ and Stokes $U$, normalized using the median intensity observed in the line core (Table 4.4). We defined the line core as the line rest wavelength ± 25 km s$^{-1}$, after rotating the data into the stellar reference frame and correcting for stellar motion (see above). We chose a broad velocity range for our calculation to accommodate the variability observed in the line. Weighting by uncertainties emphasized core data with strong signal and effectively eliminated spurious data from the average. Line core average position angles were also calculated using the error–weighted average Stokes $Q$ and Stokes $U$ (Table 4.5). We rotated angles greater than 150° so that high angles are represented as low angles in this work; a position angle on the sky of 180° is equivalent to 0° in our treatment of PA.

### 4.3.6 Line selection

We determined a global standard deviation for Stokes $Q$ and Stokes $U$ by creating a mask of featureless continuum for the range of wavelengths 400 nm to 900 nm. We identified polarization peaks that reached ≥4 times the global Stokes $Q$ standard deviation and where more than one peak was present in the line (fell within ~1 Å of a neighbor peak). These data were identified as “strong” polarization. Once the polarization signals exceeding the threshold value were identified, we plotted the spectral feature, classified each by the atomic transition and calculated the equivalent width of the spectral absorption feature and of the polarized flux as above.
We concentrated only on those spectral lines free of blends in the intensity spectrum, and with unambiguous classification and equivalent width measurement. Transition data for these polarized lines are listed in Table 4.6. In the first eight columns of Table 4.6 we list the element, the laboratory wavelength, and the lower and upper configuration, terms and $J$ value of the transition. The energies are listed in columns nine and ten. In column eleven we list the Einstein coefficients for spontaneous emission. In the last two columns we list the oscillator strength, $f_{ik}$, and $\log(gf)$.

Line polarization may arise from resonance scattering at atomic dipole transitions in the presence of some anisotropy. The polarization may occur in the line–forming region of a stellar atmosphere if collisions are not dominant (non–LTE conditions); otherwise, the polarization may be associated with cooler, outer layers of a stellar atmosphere, given some anisotropy. The resonance scattering polarization observed at the solar limb is modulated by the presence of magnetic fields (e.g. the Hanle and Zeeman effects; Stenflo (2005)). Magnetic fields are not a significant contributor to the polarization features observed in $\varepsilon$ Aurigae spectra (Landstreet, private comm.).

Abundances are generally assumed to be solar for $\varepsilon$ Aurigae (Sadakane et al., 2010). The level populations are driven by the condition (e.g. temperature, pressure) of the gas along the line–of–sight. Modeling linear polarization using a full radiative transfer solution is beyond the scope of this paper, but the results reported here may be helpful to those researchers engaged in such model–building.
4.4 Results and analysis: total flux spectra

The F0 star has been observed to be variable in spectral features as well as in brightness, continuum polarization (e.g. Coyne, 1972; Henson, 1989; Cole, 2012) and line polarization (Geise et al., 2012). We observe large variability in the line shape and equivalent width (EW) in our ESPaDOnS out-of-eclipse spectra (Fig. 4.1). Absorption features velocity-shift with the orbital motion of the F0 star (single line spectroscopic binary, SB1). Polarization peaks consistently correspond to the line core absorption (0 km s\(^{-1}\) ± 25 km s\(^{-1}\)) in the F0 star reference frame and may be attributed to the F0 star (Fig. 4.2).

We find an underlying absorption feature in K \(\lambda 769.896\) nm, a spectral line generally attributed to interstellar absorption. The stellar component is small, but it contributes measurably to the equivalent width of the line (see below). This feature was observed because of the high resolution (65 000 Donati et al. (2006)) of ESPaDOnS spectra.

4.4.1 K I (766.490 nm, 769.896 nm)

The resonance doublet of neutral potassium K I (766.490 nm, 769.896 nm) has an interstellar component whose strength is somewhat dependent upon distance (Hobbs, 1974). Terrestrial O\(_2\) lines from the A–band occur in the same wavelength span as the K I lines (Kurucz, 2011). These telluric lines shift in wavelength by epoch and are sometimes blended with the neutral potassium lines. The stronger K I line at 766.490 nm is generally more affected by tellurians than the weaker line at 769.896 nm. All of our out-of-eclipse K I 766.490 nm spectra are contaminated by telluric features.
The K i 769.896 nm line is red–shifted from the rest wavelength in our ESPaDOnS pre–eclipse observations. The line is not symmetric, but consists of a weaker component redward of a sharp deeper component. Both of these components are likely interstellar because the shape of the combined line does not change appreciably in our out–of–eclipse observations even though the radial velocity of the F0 star changes more than 6 km s\(^{-1}\) from our first pre–eclipse observation in 2003 to our last pre–eclipse observation in 2009 (see Table 4.1). We analyzed the line in the frame of reference of the line rest wavelength, not at the F0 star or any presumed disk reference frame, because the interstellar components appear fixed at the line rest wavelength. Any velocity shifts noted in the line would then be associated with the motion of the components of the system.

We observe a small variability in the blue wing of the K i 769.896 nm line in our out–of–eclipse spectra. The change in the line wing is probably not a spurious result of the pipeline reduction because it is greater than 3 sigma of the line normalization variability measured in the nearby continuum. We created an error–weighted average spectrum using four sequential observations that did not exhibit deepening in the wing. We normalized each of our observations to this averaged spectrum and uncovered a broad underlying weak absorption that appeared variable in our observations. We fit a Gaussian function to the binned data and note that the Gaussian centroid shifted toward the blue as the F0 star radial velocity also shifted toward the blue (decreasing positive) with each epoch approaching eclipse. The reduced chi square for these fits is poor, largely due to poor resolution in the line core and a residual asymmetry in the red wing possibly introduced by our choice of “normal” spectrum. The fit is excellent in the blue wing, however, our primary region of interest. Blue wing variability does not appear in any spectra after first contact.
We believe this feature is associated with the F0 star and may be a wind signature (see Fig. 4.3).

### 4.5 Results and analysis: spectropolarimetry

More than 500 atomic transitions have been observed in absorption in ε Aurigae spectra (e.g. Hack, 1959; Strassmeier et al., 2014). About 10% of those transitions exhibit more than one significant ($>4\sigma$) polarization peak in out–of–eclipse spectra (Table 4.4). The polarization is associated with the line core and is velocity–shifted with the F0 star motion. Linear polarization is observed in medium and strong absorption lines with strong resonance transitions. The line absorption is variable on at least the $\sim$2 month timeframe of our out–of–eclipse spectra. Polarization position angles average near 0° (low angles) across the line for most transitions (Fig 4.4). A few atomic transitions exhibit position angles that average $\geq 90°$ (high angles). Position angles are presented in Table 4.5. We measured the integrated polarized flux, or scattered light, for each feature with more than one polarization peak greater than $4\sigma$ (Fig. 4.5, Table 4.3). Polarized flux is also variable on at least a $\sim$2 month timescale.

The strongest polarization occurs in atomic transitions of singly–ionized iron and titanium (Table 4.6). Most of the strongly–polarized transitions begin from an electron in an $s$ orbital that transitions to a higher energy $p$ orbital and back. A few transitions are $p$ to $s$. The transitions are largely quantum mechanically–allowed transitions, except for one metastable (semi–forbidden) transition of Fe II (473.14 nm). All the transitions involved a parity change. No magnetic effects are observed in polarization and $L – S$ coupling would be appropriate to describe the atomic states of the observed transitions. Most of the observed polarized lines in ε Aurigae are not identified as strongly polarized in the Second Solar spectrum.
(Stenflo and Keller, 1997), except for the Ca i line (422.674 nm) and H i (Hα; 656.280 nm) (Belluzzi and Landi Degl’Innocenti, 2009). However, our Sun and ε Aurigae have very different spectral types and should exhibit different atomic level populations and possibly different polarization mechanisms.

4.5.1 Hydrogen

The Balmer lines, Hα (656.280 nm) through Hη (383.84 nm), are resolved in ESPaDOnS spectra (wavelength range ~370 nm to 1050 nm). Polarization is not observed for hydrogen transitions shortward of Hδ, possibly because the CCD is less sensitive in the blue and the spectra were noisier. Hα has been observed to be highly variable in out-of-eclipse spectra (Schanne, 2007). We also observe variability in the line, especially in the blue emission wing in our ESPaDOnS spectra. A position angle of ≥ 90° is associated with the line core polarization in out-of-eclipse spectra. Wing polarization when present is observed at low position angles near 0° (Table 4.5). We observe polarization peaks in Hβ and Hγ (Fig. 4.11) and polarized flux above the continuum in Hβ (Table 4.3). Position angles corresponding to polarization in Hβ and Hγ are near 0°.

4.5.2 Polarization in a remarkable out-of-eclipse Hα profile variation

Chadima et al. (2011) observed a broad blue-shifted additional absorption in Hα in two Dominion Astronomical Observatory (DAO) spectra dated 2005–09–23 and 2005–11–06. The additional absorption is also observed in an ESPaDOnS spectrum dated 2006–02–08 (Harrington and Kuhn, 2009). These observations were made more than two years before the photometric eclipse began (on or about 2009–08–16). Chadima et al. (2011) attributed this absorption feature to a transient outflow
from the F0 star or from localized circumstellar material in the line–of–sight with an RV of about \(-40 \text{ km s}^{-1}\) relative to the primary.

The intensity profile and polarization peaks for the ESPaDOnS observation are plotted in Fig 4.8. The line core depth is notably shallower than other “normal” epochs; the line is shallower than the broadened but shallow spectra noted by Hack (1959). The polarization peaks associated with the blue–shifted absorption are less pronounced than the line core polarization peaks, even though the absorption is deeper. The largest polarization peak in the blue wing is off–center by about \(+10 \text{ km s}^{-1}\) from the deepest part of the absorption feature.

The position angles also differ greatly between the wing and core (Fig 4.9). The position angle associated with the line core polarization averages near 90°, while the blue wing is polarized at low angles near 0°. It is interesting to note that the red wing is also polarized at low angles near 0° with additional absorption observable in the far red wing (~30 - 70 km s\(^{-1}\)).

Few other lines in the 2006–02–08 spectrum exhibit significant polarization peaks (Table 4.4). This suggests that the underlying photosphere is essentially symmetric at this time and that the additional absorption arises from velocity–shifted material high in the stellar atmosphere. We observe more absorption in the H\(\alpha\) blue wing than in the line core, but not more scattering, suggesting that the velocity–shifted scattering region is more symmetric than the regions that contribute to the H\(\alpha\) line core polarization. The star is noticeably dimmer during this epoch, perhaps because of a cooler outer atmosphere (Table 4.1). We also note that all the strong and medium–strength lines in this ESPaDOnS spectrum are broadened in this epoch with slightly blue–shifted line cores. Hack (1959) found that a larger macrotur-
bulence term was required to model broadened spectral features compared to the narrow deep lines observed at other times.

A similar blue–shifted polarization feature is observed in Hβ and Hγ; the RV offset of the polarization from the line core (−40 km s\(^{-1}\)) is similar between the three Balmer transitions. The polarization associated with the additional absorption is weaker in Hβ and Hγ than in Hα but is present above the noise (Fig 4.11). The polarization position angles in the blue wing of these lines also average near 0° (Table 4.5).

4.6 Discussion and conclusions

Persistent variable linear polarization in ESPaDOnS out–of–eclipse spectra suggests that some anisotropy exists associated with the F0 star in the system. The epoch of greatest polarization (2008–10–18) coincides with a large V magnitude (> 3.0), which suggests the star is dimmer/cooler than average at this time. However, our time coverage is poor, so these phenomena may be unrelated. The position angles associated with the polarized lines suggests that the anisotropy is likely an equatorial density enhancement high in the stellar atmosphere or in a circumstellar ring surrounding the star. Others have proposed the presence of an ionized ring to explain the observed variable H\(\alpha\) emission (Tan, 1985; Cha et al., 1994). Kemp et al. (1986) modeled an equatorial pulsation zone and an exposed hotter stellar pole to account for changes observed in continuum polarization during the prior eclipse (1984–1986).

We observe linear polarization in velocity–shifted hydrogen absorption with a position angle of near 0° in our 2006–02–08 data. Assuming optically thin material, this position angle suggests an equatorial enhancement (of about 0.5%) in the out-
flow gas. Models of polarized systems suggest that scattering is most likely to occur in the region a few to several radii away from the illuminating star (e.g. Harrington and Kuhn, 2009). We believe an anisotropy exists high in the F0 star stellar atmosphere because the less deep Hα line core observed in 2006 remains polarized even as the upper layers of the star were velocity–shifted. However, deeper layers probed by weak lines do not show polarization at our resolution, limiting the anisotropy to the upper atmosphere. It is possible that the outflow event may have disrupted the region responsible for persistent polarization because there are few polarized lines observed in that epoch. Alternatively, the two phenomena are unrelated and the outflow happened to occur during a time of low/no polarization.

Chadima et al. (2011) noted that the Hα central depth began to deepen about 3 years before the 2008–2011 eclipse. The authors attributed the observed change to the line core absorption to circumstellar material associated with the secondary star occulting the primary F0 star well in advance of photometric eclipse. We observe that the line core absorption is greatly reduced in our 2006–02–08 observation and is also reduced in 2008–08–25 and 2008–10–18 compared to our average spectrum (averaged over 2008–12–07, 2008–12–08, 2008–12–09, 2008–12–10). However, we propose that the change to the line core depth may be related to the unusual blue–shift in absorption and not to a leading edge of gas from the eclipsing disk. In this scenario, the lines would first be blue–shifted during an outflow event; the blue absorption would decrease and line core absorption increase as the outflow decreased with time. An increase in red wing absorption might also be observed as the (presumed pulsation) energy dissipates and the bound gas falls back into the gravitational potential of the star. We do observe a broadened red wing in 2006–02–08 (Fig 4.9) with a position angle near 0° (Fig 4.8). The red wing near the line core (25 km s$^{-1}$ to 40 km s$^{-1}$) is polarized coherently (small observed scatter) at

McLean (1979) proposed that complex patterns of variation in line profile polarizations should be observable in all stellar envelopes undergoing large-scale mass motions irrespective of the size of the embedded star. In these models, the circumstellar structure is spatially resolved by the Doppler broadening of envelope lines. We have insufficient coverage of the full orbit of the ε Aurigae system, but predict that the F0 star should exhibit polarization throughout the orbit as long as the lines are observed to be broadened. It may also be possible to validate the underlying cause of the line polarization by observing other analogue systems whose lines are severely Doppler broadened. One possible clue to the existence of a polarized envelope may be the presence of Hα emission because both phenomena are present in ε Aurigae. Finally, we intend to remove the out-of-eclipse polarization described here from our ESPaDOnS in-eclipse observations in an upcoming paper (Geise 2015, in prep., see Chapter 5) as a next step in our analysis.

4.7 Afterword

This work is in preparation for submission: Kathleen Geise, Robert Stencel* & Nadine Manset*, 2015.

*Based on observations obtained at the Canada-France-Hawaii Telescope (CFHT) which is operated by the National Research Council of Canada, the Institut National des Sciences de l’Univers of the Centre National de la Recherche Scientifique of France, and the University of Hawaii.
Table 4.1. Log of Observations (out–of–eclipse)

<table>
<thead>
<tr>
<th>UT Date</th>
<th>RJD&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Phase&lt;sup&gt;b&lt;/sup&gt;</th>
<th>RV&lt;sup&gt;b&lt;/sup&gt; [km s&lt;sup&gt;−1&lt;/sup&gt;]</th>
<th>V mag&lt;sup&gt;c&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006 Feb 08</td>
<td>3774.92</td>
<td>0.926</td>
<td>13.99</td>
<td>3.0849 ± 0.002</td>
</tr>
<tr>
<td>2008 Aug 25</td>
<td>4704.04</td>
<td>0.019</td>
<td>9.00</td>
<td>3.008 ± 0.009</td>
</tr>
<tr>
<td>2008 Oct 18</td>
<td>4757.92</td>
<td>0.025</td>
<td>8.40</td>
<td>3.0437 ± 0.0034</td>
</tr>
<tr>
<td>2008 Dec 07&lt;sup&gt;d&lt;/sup&gt;</td>
<td>4807.82</td>
<td>0.030</td>
<td>7.82</td>
<td>2.9560 ± 0.0010</td>
</tr>
<tr>
<td>2008 Dec 08&lt;sup&gt;d&lt;/sup&gt;</td>
<td>4808.83</td>
<td>0.030</td>
<td>7.81</td>
<td>...</td>
</tr>
<tr>
<td>2008 Dec 09&lt;sup&gt;d&lt;/sup&gt;</td>
<td>4809.83</td>
<td>0.030</td>
<td>7.80</td>
<td>...</td>
</tr>
<tr>
<td>2008 Dec 10&lt;sup&gt;d&lt;/sup&gt;</td>
<td>4810.83</td>
<td>0.030</td>
<td>7.79</td>
<td>2.9934</td>
</tr>
<tr>
<td>2008 Dec 16&lt;sup&gt;d&lt;/sup&gt;</td>
<td>4817.05</td>
<td>0.031</td>
<td>7.71</td>
<td>2.962 ± 0.055</td>
</tr>
<tr>
<td>2009 Feb 13&lt;sup&gt;e&lt;/sup&gt;</td>
<td>4875.71</td>
<td>0.036</td>
<td>7.01</td>
<td>3.036 ± 0.006</td>
</tr>
<tr>
<td>2009 Feb 14&lt;sup&gt;e&lt;/sup&gt;</td>
<td>4876.70</td>
<td>0.037</td>
<td>7.00</td>
<td>3.023 ± 0.004</td>
</tr>
<tr>
<td>2009 Feb 17&lt;sup&gt;e&lt;/sup&gt;</td>
<td>4879.85</td>
<td>0.037</td>
<td>6.96</td>
<td>3.060 ± 0.004</td>
</tr>
</tbody>
</table>

<sup>a</sup>RJD = Heliocentric Julian Date - 2450000

<sup>b</sup>F0 star, calculated using the ephemeris from Stefanik et al. (2010) 2434723 + 9896.0E

<sup>c</sup>Data from the American Association of Variable Star Observers, online at http://www.AAVSO.org

<sup>d</sup>These observations were used to create an error–weighted average “normal” spectrum dated 2008–12–07.

<sup>e</sup>These observations were used to create an error–weighted average spectrum dated 2009–02–13.
Table 4.2: Equivalent widths

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Species</th>
<th>Range</th>
<th>20060208 Beg (nm)</th>
<th>20060208 End (nm)</th>
<th>20060208 EW (mA)</th>
<th>20080825 EW (mA)</th>
<th>20081018 EW (mA)</th>
<th>20081207a EW (mA)</th>
<th>20080213b EW (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>410.173</td>
<td>H I</td>
<td>409.57</td>
<td>410.77</td>
<td>1716</td>
<td>1722</td>
<td>1724</td>
<td>1770</td>
<td>1703</td>
<td></td>
</tr>
<tr>
<td>422.673</td>
<td>Ca I</td>
<td>422.60</td>
<td>422.83</td>
<td>606</td>
<td>490</td>
<td>561</td>
<td>460</td>
<td>584</td>
<td></td>
</tr>
<tr>
<td>422.733</td>
<td>Ti II</td>
<td>422.60</td>
<td>422.83</td>
<td>⋯</td>
<td>⋯</td>
<td>⋯</td>
<td>⋯</td>
<td>⋯</td>
<td></td>
</tr>
<tr>
<td>423.316</td>
<td>Fe II</td>
<td>423.10</td>
<td>423.50</td>
<td>897</td>
<td>805</td>
<td>828</td>
<td>800</td>
<td>821</td>
<td></td>
</tr>
<tr>
<td>434.047</td>
<td>H I</td>
<td>433.88</td>
<td>434.28</td>
<td>1919</td>
<td>1925</td>
<td>1931</td>
<td>1947</td>
<td>1884</td>
<td></td>
</tr>
<tr>
<td>438.538</td>
<td>Fe II</td>
<td>438.47</td>
<td>438.62</td>
<td>590</td>
<td>578</td>
<td>588</td>
<td>605</td>
<td>573</td>
<td></td>
</tr>
<tr>
<td>444.380</td>
<td>Ti II</td>
<td>444.25</td>
<td>444.55</td>
<td>1061</td>
<td>963</td>
<td>1003</td>
<td>952</td>
<td>998</td>
<td></td>
</tr>
<tr>
<td>444.456</td>
<td>Ti II</td>
<td>444.25</td>
<td>444.55</td>
<td>⋯</td>
<td>⋯</td>
<td>⋯</td>
<td>⋯</td>
<td>⋯</td>
<td></td>
</tr>
<tr>
<td>446.849</td>
<td>Ti II</td>
<td>446.71</td>
<td>447.00</td>
<td>899</td>
<td>792</td>
<td>818</td>
<td>781</td>
<td>813</td>
<td></td>
</tr>
<tr>
<td>450.127</td>
<td>Ti II</td>
<td>449.95</td>
<td>450.27</td>
<td>735</td>
<td>669</td>
<td>690</td>
<td>673</td>
<td>669</td>
<td></td>
</tr>
<tr>
<td>450.828</td>
<td>Fe II</td>
<td>450.67</td>
<td>450.95</td>
<td>604</td>
<td>572</td>
<td>574</td>
<td>586</td>
<td>565</td>
<td></td>
</tr>
<tr>
<td>451.533</td>
<td>Fe II</td>
<td>451.40</td>
<td>451.65</td>
<td>540</td>
<td>530</td>
<td>532</td>
<td>544</td>
<td>520</td>
<td></td>
</tr>
<tr>
<td>452.022</td>
<td>Fe II</td>
<td>451.91</td>
<td>452.14</td>
<td>530</td>
<td>519</td>
<td>520</td>
<td>533</td>
<td>511</td>
<td></td>
</tr>
<tr>
<td>452.263</td>
<td>Fe II</td>
<td>452.12</td>
<td>452.39</td>
<td>631</td>
<td>620</td>
<td>613</td>
<td>632</td>
<td>597</td>
<td></td>
</tr>
<tr>
<td>453.396</td>
<td>Ti II</td>
<td>453.26</td>
<td>453.52</td>
<td>788</td>
<td>738</td>
<td>734</td>
<td>736</td>
<td>724</td>
<td></td>
</tr>
<tr>
<td>456.376</td>
<td>Ti II</td>
<td>456.25</td>
<td>456.50</td>
<td>739</td>
<td>675</td>
<td>690</td>
<td>675</td>
<td>678</td>
<td></td>
</tr>
<tr>
<td>458.820</td>
<td>Cr II</td>
<td>458.67</td>
<td>458.90</td>
<td>506</td>
<td>466</td>
<td>481</td>
<td>473</td>
<td>473</td>
<td></td>
</tr>
<tr>
<td>459.205</td>
<td>Cr II</td>
<td>459.10</td>
<td>459.30</td>
<td>301</td>
<td>271</td>
<td>291</td>
<td>274</td>
<td>297</td>
<td></td>
</tr>
<tr>
<td>461.881</td>
<td>Cr II</td>
<td>461.75</td>
<td>461.96</td>
<td>437</td>
<td>407</td>
<td>424</td>
<td>410</td>
<td>419</td>
<td></td>
</tr>
<tr>
<td>462.933</td>
<td>Fe II</td>
<td>462.78</td>
<td>463.08</td>
<td>625</td>
<td>598</td>
<td>607</td>
<td>611</td>
<td>598</td>
<td></td>
</tr>
<tr>
<td>467.041</td>
<td>Sc II</td>
<td>466.89</td>
<td>467.19</td>
<td>387</td>
<td>330</td>
<td>367</td>
<td>323</td>
<td>373</td>
<td></td>
</tr>
</tbody>
</table>

Continued on Next Page...
<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Species</th>
<th>Range Beg (nm)</th>
<th>End (nm)</th>
<th>EW (mA)</th>
<th>EW (mA)</th>
<th>EW (mA)</th>
<th>EW (mA)</th>
<th>EW (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>473.144</td>
<td>Fe II</td>
<td>473.00</td>
<td>473.28</td>
<td>373</td>
<td>356</td>
<td>368</td>
<td>360</td>
<td>368</td>
</tr>
<tr>
<td>480.509</td>
<td>Ti II</td>
<td>480.35</td>
<td>480.65</td>
<td>441</td>
<td>390</td>
<td>422</td>
<td>385</td>
<td>426</td>
</tr>
<tr>
<td>486.135</td>
<td>H I</td>
<td>485.90</td>
<td>486.30</td>
<td>1632</td>
<td>1614</td>
<td>1587</td>
<td>1553</td>
<td>1538</td>
</tr>
<tr>
<td>492.392</td>
<td>Fe II</td>
<td>492.20</td>
<td>492.65</td>
<td>975</td>
<td>884</td>
<td>855</td>
<td>852</td>
<td>850</td>
</tr>
<tr>
<td>493.408</td>
<td>Ba II</td>
<td>493.20</td>
<td>493.60</td>
<td>266</td>
<td>189</td>
<td>236</td>
<td>164</td>
<td>249</td>
</tr>
<tr>
<td>495.760</td>
<td>Fe I</td>
<td>495.50</td>
<td>496.02</td>
<td>314</td>
<td>268</td>
<td>294</td>
<td>249</td>
<td>317</td>
</tr>
<tr>
<td>501.844</td>
<td>Fe II</td>
<td>501.60</td>
<td>502.10</td>
<td>1111</td>
<td>980</td>
<td>955</td>
<td>928</td>
<td>958</td>
</tr>
<tr>
<td>512.916</td>
<td>Ti II</td>
<td>512.80</td>
<td>513.00</td>
<td>338</td>
<td>282</td>
<td>319</td>
<td>282</td>
<td>312</td>
</tr>
<tr>
<td>516.732</td>
<td>Mg I</td>
<td>516.60</td>
<td>516.78</td>
<td>369</td>
<td>277</td>
<td>322</td>
<td>241</td>
<td>334</td>
</tr>
<tr>
<td>516.890d</td>
<td>Fe I</td>
<td>516.77</td>
<td>517.09</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>516.903</td>
<td>Fe II</td>
<td>516.77</td>
<td>517.09</td>
<td>1111</td>
<td>963</td>
<td>917</td>
<td>926</td>
<td>920</td>
</tr>
<tr>
<td>517.268</td>
<td>Mg I</td>
<td>517.05</td>
<td>517.45</td>
<td>529</td>
<td>452</td>
<td>497</td>
<td>428</td>
<td>520</td>
</tr>
<tr>
<td>518.360</td>
<td>Mg I</td>
<td>518.20</td>
<td>518.46</td>
<td>474</td>
<td>418</td>
<td>448</td>
<td>400</td>
<td>456</td>
</tr>
<tr>
<td>519.757</td>
<td>Fe II</td>
<td>519.60</td>
<td>519.90</td>
<td>527</td>
<td>493</td>
<td>511</td>
<td>503</td>
<td>478</td>
</tr>
<tr>
<td>523.732</td>
<td>Cr II</td>
<td>523.57</td>
<td>523.88</td>
<td>316</td>
<td>290</td>
<td>317</td>
<td>296</td>
<td>301</td>
</tr>
<tr>
<td>527.600</td>
<td>Fe II</td>
<td>527.35</td>
<td>527.85</td>
<td>878</td>
<td>829</td>
<td>857</td>
<td>835</td>
<td>817</td>
</tr>
<tr>
<td>531.678</td>
<td>Fe II</td>
<td>531.45</td>
<td>531.90</td>
<td>802</td>
<td>754</td>
<td>760</td>
<td>763</td>
<td>719</td>
</tr>
<tr>
<td>536.275</td>
<td>Fe II</td>
<td>536.15</td>
<td>536.40</td>
<td>391</td>
<td>375</td>
<td>380</td>
<td>386</td>
<td>354</td>
</tr>
<tr>
<td>552.679</td>
<td>Sc II</td>
<td>552.55</td>
<td>552.80</td>
<td>397</td>
<td>332</td>
<td>376</td>
<td>314</td>
<td>380</td>
</tr>
<tr>
<td>645.638</td>
<td>Fe II</td>
<td>645.45</td>
<td>645.80</td>
<td>528</td>
<td>464</td>
<td>503</td>
<td>481</td>
<td>466</td>
</tr>
<tr>
<td>656.280</td>
<td>H I</td>
<td>655.84</td>
<td>656.71</td>
<td>1215</td>
<td>904</td>
<td>918</td>
<td>581</td>
<td>530</td>
</tr>
<tr>
<td>769.896e</td>
<td>K I</td>
<td>769.79</td>
<td>770.00</td>
<td>203</td>
<td>181</td>
<td>185</td>
<td>178</td>
<td>216</td>
</tr>
<tr>
<td>777.149</td>
<td>O I</td>
<td>776.95</td>
<td>777.33</td>
<td>970</td>
<td>937</td>
<td>932</td>
<td>934</td>
<td>909</td>
</tr>
</tbody>
</table>

Continued on Next Page...
Table 4.2 – Continued

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Species</th>
<th>Range 20060208</th>
<th>20080825</th>
<th>20081018</th>
<th>20081207(^a)</th>
<th>20081207(^b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>777.149(^f)</td>
<td>O I</td>
<td>776.95</td>
<td>777.80</td>
<td>2330</td>
<td>2317</td>
<td>2297</td>
</tr>
</tbody>
</table>

Note: The data tabled here are the equivalent width (EW) of total flux directly-integrated across the line (see text). Uncertainties < 1 mA throughout.


\(^c\) Blend; not a significant contributor to polarization.

\(^d\) Blend; may contribute to polarization.

\(^e\) Included for completeness.

\(^f\) Includes all 3 transitions of the O I triplet.
<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Species</th>
<th>20060208 pf EW (mA)</th>
<th>20080825 pf EW (mA)</th>
<th>20081018 pf EW (mA)</th>
<th>20081207 (^a) pf EW (mA)</th>
<th>20080213 (^b) pf EW (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>410.173</td>
<td>H I</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>422.673</td>
<td>Ca I</td>
<td>...</td>
<td>1.9 ± 0.3</td>
<td>...</td>
<td>3.6 ± 0.2</td>
<td>4.6 ± 0.3</td>
</tr>
<tr>
<td>423.316</td>
<td>Fe II</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>434.947</td>
<td>H I</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>438.538</td>
<td>Fe II</td>
<td>...</td>
<td>0.6 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>0.7 ± 0.2</td>
</tr>
<tr>
<td>444.380</td>
<td>Ti II</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>444.456(^c)</td>
<td>Ti II</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>446.849</td>
<td>Ti II</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>0.8 ± 0.2</td>
<td>...</td>
</tr>
<tr>
<td>450.127</td>
<td>Ti II</td>
<td>...</td>
<td>1.2 ± 0.3</td>
<td>...</td>
<td>1.0 ± 0.2</td>
<td>1.3 ± 0.3</td>
</tr>
<tr>
<td>450.828</td>
<td>Fe II</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>0.9 ± 0.2</td>
<td>...</td>
</tr>
<tr>
<td>451.332</td>
<td>Fe II</td>
<td>...</td>
<td>1.0 ± 0.2</td>
<td>...</td>
<td>1.1 ± 0.2</td>
<td>...</td>
</tr>
<tr>
<td>452.022</td>
<td>Fe II</td>
<td>...</td>
<td>1.0 ± 0.2</td>
<td>1.1 ± 0.3</td>
<td>0.7 ± 0.2</td>
<td>1.0 ± 0.2</td>
</tr>
<tr>
<td>452.263</td>
<td>Fe II</td>
<td>...</td>
<td>0.6 ± 0.2</td>
<td>1.3 ± 0.3</td>
<td>0.9 ± 0.2</td>
<td>...</td>
</tr>
<tr>
<td>453.396</td>
<td>Ti II</td>
<td>1.0 ± 0.3</td>
<td>1.2 ± 0.2</td>
<td>1.2 ± 0.3</td>
<td>1.0 ± 0.2</td>
<td>0.7 ± 0.2</td>
</tr>
<tr>
<td>456.376</td>
<td>Ti II</td>
<td>...</td>
<td>0.9 ± 0.2</td>
<td>...</td>
<td>0.8 ± 0.2</td>
<td>0.7 ± 0.2</td>
</tr>
<tr>
<td>458.820</td>
<td>Cr II</td>
<td>1.2 ± 0.4</td>
<td>1.1 ± 0.2</td>
<td>1.1 ± 0.3</td>
<td>0.9 ± 0.2</td>
<td>0.9 ± 0.3</td>
</tr>
<tr>
<td>459.205</td>
<td>Cr II</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>461.881</td>
<td>Cr II</td>
<td>...</td>
<td>1.0 ± 0.2</td>
<td>...</td>
<td>0.6 ± 0.2</td>
<td>...</td>
</tr>
<tr>
<td>462.933</td>
<td>Fe II</td>
<td>...</td>
<td>1.0 ± 0.2</td>
<td>1.1 ± 0.3</td>
<td>0.7 ± 0.2</td>
<td>...</td>
</tr>
<tr>
<td>467.041</td>
<td>Sc II</td>
<td>...</td>
<td>...</td>
<td>1.0 ± 0.3</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>473.144</td>
<td>Fe II</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>480.509</td>
<td>Ti II</td>
<td>0.8 ± 0.2</td>
<td>1.1 ± 0.3</td>
<td>1.0 ± 0.2</td>
<td>1.2 ± 0.2</td>
<td>...</td>
</tr>
<tr>
<td>486.135</td>
<td>H I</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>492.392</td>
<td>Fe II</td>
<td>...</td>
<td>1.0 ± 0.3</td>
<td>...</td>
<td>0.9 ± 0.2</td>
<td>...</td>
</tr>
<tr>
<td>493.408</td>
<td>Ba II</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>495.760</td>
<td>Fe I</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>501.844</td>
<td>Fe II</td>
<td>1.4 ± 0.4</td>
<td>1.8 ± 0.3</td>
<td>1.3 ± 0.4</td>
<td>0.7 ± 0.2</td>
<td>0.9 ± 0.3</td>
</tr>
<tr>
<td>512.916</td>
<td>Ti II</td>
<td>...</td>
<td>1.0 ± 0.2</td>
<td>1.3 ± 0.2</td>
<td>0.6 ± 0.2</td>
<td>...</td>
</tr>
<tr>
<td>516.732</td>
<td>Mg I</td>
<td>...</td>
<td>0.6 ± 0.2</td>
<td>1.0 ± 0.2</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>516.890(^d)</td>
<td>Fe I</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>516.903</td>
<td>Fe II</td>
<td>1.2 ± 0.3</td>
<td>1.6 ± 0.2</td>
<td>1.2 ± 0.3</td>
<td>0.9 ± 0.2</td>
<td>1.4 ± 0.20</td>
</tr>
<tr>
<td>517.268</td>
<td>Mg I</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>518.360</td>
<td>Mg I</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>519.757</td>
<td>Fe II</td>
<td>1.0 ± 0.2</td>
<td>1.1 ± 0.3</td>
<td>...</td>
<td>0.7 ± 0.2</td>
<td>...</td>
</tr>
<tr>
<td>523.732</td>
<td>Cr II</td>
<td>...</td>
<td>0.8 ± 0.2</td>
<td>1.2 ± 0.3</td>
<td>0.6 ± 0.2</td>
<td>...</td>
</tr>
<tr>
<td>527.600</td>
<td>Fe II</td>
<td>...</td>
<td>1.2 ± 0.3</td>
<td>...</td>
<td>0.8 ± 0.2</td>
<td>...</td>
</tr>
</tbody>
</table>

Continued on Next Page...
Table 4.3 – Continued

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Species</th>
<th>pf EW</th>
<th>pf EW</th>
<th>pf EW</th>
<th>pf EW</th>
<th>pf EW</th>
</tr>
</thead>
<tbody>
<tr>
<td>531.678</td>
<td>Fe II</td>
<td>…</td>
<td>1.4 ± 0.2</td>
<td>1.8 ± 0.3</td>
<td>1.1 ± 0.2</td>
<td>0.9 ± 0.3</td>
</tr>
<tr>
<td>536.275</td>
<td>Fe II</td>
<td>0.9 ± 0.3</td>
<td>1.3 ± 0.2</td>
<td>1.2 ± 0.3</td>
<td>0.9 ± 0.2</td>
<td>0.9 ± 0.2</td>
</tr>
<tr>
<td>552.679</td>
<td>Sc II</td>
<td>…</td>
<td>0.9 ± 0.2</td>
<td>1.5 ± 0.3</td>
<td>0.6 ± 0.2</td>
<td>0.6 ± 0.2</td>
</tr>
<tr>
<td>645.638</td>
<td>Fe II</td>
<td>…</td>
<td>1.7 ± 0.2</td>
<td>…</td>
<td>0.8 ± 0.2</td>
<td>0.6 ± 0.2</td>
</tr>
<tr>
<td>656.280</td>
<td>H I</td>
<td>4.3 ± 0.7</td>
<td>2.0 ± 0.5</td>
<td>3.2 ± 0.6</td>
<td>2.8 ± 0.3</td>
<td>1.7 ± 0.5</td>
</tr>
<tr>
<td>777.149</td>
<td>O I</td>
<td>…</td>
<td>…</td>
<td>…</td>
<td>…</td>
<td>0.9 ± 0.2</td>
</tr>
</tbody>
</table>

Note: The data tabled here are the equivalent width of polarized flux calculated using the same wavelength range as EW (see text). Polarized flux less than 3σ omitted.


c Blend; not a significant contributor to polarization.

d Blend; may contribute to polarization.
<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Species</th>
<th>20060208 %p</th>
<th>20080825 %p</th>
<th>20081018 %p</th>
<th>20081207 %p</th>
<th>20080213 %p</th>
</tr>
</thead>
<tbody>
<tr>
<td>410.173</td>
<td>H I</td>
<td>0.58 ± 0.02</td>
<td>0.41 ± 0.02</td>
<td>0.35 ± 0.02</td>
<td>0.36 ± 0.01</td>
<td>0.40 ± 0.02</td>
</tr>
<tr>
<td>422.673</td>
<td>Ca I</td>
<td>0.14 ± 0.03</td>
<td>0.30 ± 0.02</td>
<td>0.20 ± 0.03</td>
<td>0.77 ± 0.01</td>
<td><strong>1.09 ± 0.02</strong></td>
</tr>
<tr>
<td>422.733</td>
<td>Ti II</td>
<td>...</td>
<td>0.40 ± 0.03</td>
<td><strong>0.51 ± 0.04</strong></td>
<td>0.30 ± 0.02</td>
<td>0.32 ± 0.03</td>
</tr>
<tr>
<td>423.316</td>
<td>Fe II</td>
<td><strong>0.57 ± 0.02</strong></td>
<td>0.32 ± 0.02</td>
<td>0.53 ± 0.02</td>
<td>0.38 ± 0.01</td>
<td>0.45 ± 0.02</td>
</tr>
<tr>
<td>434.047</td>
<td>H I</td>
<td>0.10 ± 0.02</td>
<td>...</td>
<td><strong>0.20 ± 0.01</strong></td>
<td>0.16 ± 0.01</td>
<td>0.16 ± 0.01</td>
</tr>
<tr>
<td>438.538</td>
<td>Fe II</td>
<td>0.11 ± 0.02</td>
<td>0.22 ± 0.02</td>
<td><strong>0.30 ± 0.02</strong></td>
<td>0.21 ± 0.01</td>
<td>0.16 ± 0.02</td>
</tr>
<tr>
<td>444.380</td>
<td>Ti II</td>
<td>0.23 ± 0.02</td>
<td>0.21 ± 0.01</td>
<td><strong>0.31 ± 0.02</strong></td>
<td>0.19 ± 0.01</td>
<td>0.26 ± 0.01</td>
</tr>
<tr>
<td>444.456</td>
<td>Ti II</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>446.849</td>
<td>Ti II</td>
<td>0.34 ± 0.02</td>
<td>0.29 ± 0.01</td>
<td><strong>0.42 ± 0.02</strong></td>
<td>0.29 ± 0.01</td>
<td>0.27 ± 0.01</td>
</tr>
<tr>
<td>450.127</td>
<td>Ti II</td>
<td>0.42 ± 0.02</td>
<td>0.33 ± 0.02</td>
<td><strong>0.45 ± 0.02</strong></td>
<td>0.35 ± 0.01</td>
<td>0.28 ± 0.01</td>
</tr>
<tr>
<td>450.828</td>
<td>Fe II</td>
<td>0.33 ± 0.02</td>
<td>0.19 ± 0.01</td>
<td><strong>0.34 ± 0.02</strong></td>
<td>0.24 ± 0.01</td>
<td>0.25 ± 0.01</td>
</tr>
<tr>
<td>451.533</td>
<td>Fe II</td>
<td><strong>0.29 ± 0.02</strong></td>
<td>0.22 ± 0.01</td>
<td>0.27 ± 0.02</td>
<td>0.23 ± 0.01</td>
<td>0.23 ± 0.01</td>
</tr>
<tr>
<td>452.202</td>
<td>Fe II</td>
<td>0.30 ± 0.02</td>
<td>0.22 ± 0.01</td>
<td><strong>0.39 ± 0.02</strong></td>
<td>0.24 ± 0.01</td>
<td>0.23 ± 0.01</td>
</tr>
<tr>
<td>452.263</td>
<td>Fe II</td>
<td>0.35 ± 0.02</td>
<td>0.23 ± 0.01</td>
<td><strong>0.41 ± 0.02</strong></td>
<td>0.30 ± 0.01</td>
<td>0.22 ± 0.01</td>
</tr>
<tr>
<td>453.396</td>
<td>Ti II</td>
<td>0.33 ± 0.02</td>
<td>0.24 ± 0.01</td>
<td><strong>0.41 ± 0.02</strong></td>
<td>0.29 ± 0.01</td>
<td>0.30 ± 0.01</td>
</tr>
<tr>
<td>456.376</td>
<td>Ti II</td>
<td>0.29 ± 0.02</td>
<td>0.23 ± 0.01</td>
<td><strong>0.39 ± 0.02</strong></td>
<td>0.27 ± 0.01</td>
<td>0.26 ± 0.01</td>
</tr>
<tr>
<td>458.820</td>
<td>Cr II</td>
<td>0.16 ± 0.02</td>
<td>0.22 ± 0.02</td>
<td><strong>0.29 ± 0.02</strong></td>
<td>0.21 ± 0.01</td>
<td>0.20 ± 0.02</td>
</tr>
<tr>
<td>459.205</td>
<td>Cr II</td>
<td>0.10 ± 0.03</td>
<td>0.08 ± 0.02</td>
<td><strong>0.18 ± 0.02</strong></td>
<td>0.11 ± 0.01</td>
<td>0.11 ± 0.02</td>
</tr>
<tr>
<td>461.881</td>
<td>Cr II</td>
<td>0.14 ± 0.02</td>
<td>0.15 ± 0.01</td>
<td><strong>0.32 ± 0.02</strong></td>
<td>0.18 ± 0.01</td>
<td>0.14 ± 0.02</td>
</tr>
<tr>
<td>462.933</td>
<td>Fe II</td>
<td>0.28 ± 0.02</td>
<td>0.27 ± 0.01</td>
<td><strong>0.40 ± 0.02</strong></td>
<td>0.27 ± 0.01</td>
<td>0.25 ± 0.01</td>
</tr>
<tr>
<td>467.041</td>
<td>Sc II</td>
<td>0.14 ± 0.02</td>
<td>0.06 ± 0.01</td>
<td><strong>0.23 ± 0.02</strong></td>
<td>0.09 ± 0.01</td>
<td>0.19 ± 0.02</td>
</tr>
</tbody>
</table>

Continued on Next Page...
<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Species</th>
<th>20060208 %p</th>
<th>20080213 %p</th>
<th>20080825 %p</th>
<th>20081018 %p</th>
<th>20081207 %p</th>
<th>20081207 %p</th>
<th>20081207 %p</th>
</tr>
</thead>
<tbody>
<tr>
<td>473.144</td>
<td>Fe II</td>
<td>0.15 ± 0.02</td>
<td>0.12 ± 0.01</td>
<td>0.26 ± 0.02</td>
<td>0.16 ± 0.01</td>
<td>0.16 ± 0.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>480.509</td>
<td>Ti II</td>
<td>0.25 ± 0.02</td>
<td>0.11 ± 0.01</td>
<td>0.35 ± 0.02</td>
<td>0.16 ± 0.01</td>
<td>0.18 ± 0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>486.135</td>
<td>H I</td>
<td>0.06 ± 0.01</td>
<td>0.20 ± 0.01</td>
<td>0.20 ± 0.01</td>
<td>0.20 ± 0.01</td>
<td>0.26 ± 0.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>492.392</td>
<td>Fe II</td>
<td>0.28 ± 0.01</td>
<td>0.34 ± 0.01</td>
<td>0.30 ± 0.01</td>
<td>0.31 ± 0.01</td>
<td>0.28 ± 0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>493.408</td>
<td>Ba II</td>
<td>0.14 ± 0.02</td>
<td>...</td>
<td>0.22 ± 0.02</td>
<td>...</td>
<td>0.12 ± 0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>495.760</td>
<td>Fe I</td>
<td>0.13 ± 0.02</td>
<td>...</td>
<td>0.20 ± 0.02</td>
<td>...</td>
<td>0.14 ± 0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>501.844</td>
<td>Fe II</td>
<td>0.31 ± 0.01</td>
<td>0.35 ± 0.01</td>
<td>0.38 ± 0.01</td>
<td>0.23 ± 0.01</td>
<td>0.26 ± 0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>512.916</td>
<td>Ti II</td>
<td>0.08 ± 0.02</td>
<td>0.10 ± 0.01</td>
<td>0.24 ± 0.02</td>
<td>0.11 ± 0.01</td>
<td>0.12 ± 0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>516.732</td>
<td>Mg I</td>
<td>0.10 ± 0.02</td>
<td>0.05 ± 0.01</td>
<td>0.21 ± 0.02</td>
<td>0.05 ± 0.01</td>
<td>0.11 ± 0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>518.904</td>
<td>Fe I</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td></td>
<td></td>
</tr>
<tr>
<td>519.693</td>
<td>Fe II</td>
<td>0.31 ± 0.01</td>
<td>0.25 ± 0.01</td>
<td>0.35 ± 0.01</td>
<td>0.30 ± 0.01</td>
<td>0.23 ± 0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>517.268</td>
<td>Mg I</td>
<td>0.16 ± 0.02</td>
<td>0.11 ± 0.01</td>
<td>0.24 ± 0.02</td>
<td>0.09 ± 0.01</td>
<td>0.08 ± 0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>518.360</td>
<td>Mg I</td>
<td>0.21 ± 0.02</td>
<td>0.13 ± 0.01</td>
<td>0.24 ± 0.01</td>
<td>0.13 ± 0.01</td>
<td>0.15 ± 0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>519.757</td>
<td>Fe II</td>
<td>0.18 ± 0.02</td>
<td>0.18 ± 0.01</td>
<td>0.27 ± 0.01</td>
<td>0.21 ± 0.01</td>
<td>0.15 ± 0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>523.732</td>
<td>Cr II</td>
<td>0.11 ± 0.02</td>
<td>0.11 ± 0.01</td>
<td>0.21 ± 0.02</td>
<td>0.11 ± 0.01</td>
<td>0.13 ± 0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>527.600</td>
<td>Fe II</td>
<td>0.22 ± 0.01</td>
<td>0.17 ± 0.01</td>
<td>0.23 ± 0.01</td>
<td>0.18 ± 0.01</td>
<td>0.14 ± 0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>531.678</td>
<td>Fe II</td>
<td>0.23 ± 0.01</td>
<td>0.19 ± 0.01</td>
<td>0.26 ± 0.01</td>
<td>0.27 ± 0.01</td>
<td>0.15 ± 0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>536.275</td>
<td>Fe II</td>
<td>0.22 ± 0.02</td>
<td>0.18 ± 0.01</td>
<td>0.26 ± 0.02</td>
<td>0.17 ± 0.01</td>
<td>0.13 ± 0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>552.679</td>
<td>Sc II</td>
<td>0.13 ± 0.02</td>
<td>0.07 ± 0.01</td>
<td>0.19 ± 0.01</td>
<td>0.10 ± 0.01</td>
<td>0.11 ± 0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>645.638</td>
<td>Fe II</td>
<td>0.16 ± 0.01</td>
<td>0.11 ± 0.01</td>
<td>0.20 ± 0.01</td>
<td>0.13 ± 0.01</td>
<td>0.16 ± 0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>656.280</td>
<td>H I</td>
<td>0.38 ± 0.01</td>
<td>0.44 ± 0.01</td>
<td>0.59 ± 0.01</td>
<td>0.46 ± 0.01</td>
<td>0.58 ± 0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>777.149</td>
<td>O I</td>
<td>0.16 ± 0.01</td>
<td>0.08 ± 0.01</td>
<td>0.16 ± 0.01</td>
<td>0.09 ± 0.01</td>
<td>0.21 ± 0.01</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Continued on Next Page...
**Table 4.4 – Continued**

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Species</th>
<th>20060208 %p</th>
<th>20080825 %p</th>
<th>20081018 %p</th>
<th>20081207&lt;sup&gt;a&lt;/sup&gt; %p</th>
<th>20080213&lt;sup&gt;b&lt;/sup&gt; %p</th>
</tr>
</thead>
</table>

*Note:* This table contains polarization (%p) for the line core calculated from error-weighted Stokes Q, error-weighted Stokes U and median intensity, where the line core is defined as the line rest wavelength ± 25 km s<sup>−1</sup>. The data have been rotated into the stellar frame of reference and corrected for stellar motion (see text). Data with %p < 4σ were omitted. Bold-face text indicates epoch of greatest observed line core polarization.


<sup>c</sup>Blend; not a significant contributor to polarization.

<sup>d</sup>Blend; may contribute to polarization.
Table 4.5: Line core average position angle

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Species</th>
<th>20060208 PA (deg)</th>
<th>20080825 PA (deg)</th>
<th>20081018 PA (deg)</th>
<th>20081207a PA (deg)</th>
<th>20080213b PA (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>410.173</td>
<td>H I</td>
<td>2 ± 6</td>
<td>7 ± 5</td>
<td>24 ± 9</td>
<td>17 ± 4</td>
<td>11 ± 6</td>
</tr>
<tr>
<td>422.673</td>
<td>Ca I</td>
<td>108 ± 12</td>
<td>115 ± 3</td>
<td>123 ± 7</td>
<td>84 ± 1</td>
<td>68 ± 1</td>
</tr>
<tr>
<td>422.733</td>
<td>Ti II</td>
<td>6 ± 3</td>
<td>1 ± 3</td>
<td>11 ± 4</td>
<td>11 ± 2</td>
<td>4 ± 3</td>
</tr>
<tr>
<td>423.816</td>
<td>Fe II</td>
<td>4 ± 4</td>
<td>19 ± 4</td>
<td>11 ± 4</td>
<td>11 ± 2</td>
<td>4 ± 3</td>
</tr>
<tr>
<td>434.047</td>
<td>H I</td>
<td>−14 ± 22</td>
<td>37 ± 12</td>
<td>42 ± 8</td>
<td>124 ± 9</td>
<td></td>
</tr>
<tr>
<td>438.538</td>
<td>Fe II</td>
<td>−14 ± 14</td>
<td>16 ± 4</td>
<td>20 ± 4</td>
<td>12 ± 3</td>
<td>0 ± 6</td>
</tr>
<tr>
<td>444.380</td>
<td>Ti II</td>
<td>−11 ± 7</td>
<td>9 ± 5</td>
<td>9 ± 4</td>
<td>1 ± 3</td>
<td>−1 ± 4</td>
</tr>
<tr>
<td>444.456</td>
<td>Ti II</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>446.849</td>
<td>Ti II</td>
<td>−3 ± 5</td>
<td>13 ± 4</td>
<td>9 ± 3</td>
<td>9 ± 2</td>
<td>−1 ± 4</td>
</tr>
<tr>
<td>450.127</td>
<td>Ti II</td>
<td>−5 ± 4</td>
<td>20 ± 3</td>
<td>9 ± 3</td>
<td>8 ± 2</td>
<td>5 ± 3</td>
</tr>
<tr>
<td>450.828</td>
<td>Fe II</td>
<td>−9 ± 4</td>
<td>14 ± 4</td>
<td>7 ± 3</td>
<td>8 ± 2</td>
<td>4 ± 3</td>
</tr>
<tr>
<td>451.533</td>
<td>Fe II</td>
<td>−1 ± 4</td>
<td>17 ± 4</td>
<td>3 ± 4</td>
<td>4 ± 2</td>
<td>9 ± 4</td>
</tr>
<tr>
<td>452.022</td>
<td>Fe II</td>
<td>−8 ± 4</td>
<td>13 ± 4</td>
<td>7 ± 3</td>
<td>6 ± 2</td>
<td>10 ± 3</td>
</tr>
<tr>
<td>452.263</td>
<td>Fe II</td>
<td>2 ± 4</td>
<td>18 ± 4</td>
<td>6 ± 3</td>
<td>7 ± 2</td>
<td>0 ± 4</td>
</tr>
<tr>
<td>453.396</td>
<td>Ti II</td>
<td>−6 ± 4</td>
<td>23 ± 4</td>
<td>6 ± 3</td>
<td>3 ± 2</td>
<td>2 ± 3</td>
</tr>
<tr>
<td>456.376</td>
<td>Ti II</td>
<td>0 ± 5</td>
<td>12 ± 4</td>
<td>5 ± 3</td>
<td>5 ± 2</td>
<td>8 ± 4</td>
</tr>
<tr>
<td>458.820</td>
<td>Cr II</td>
<td>6 ± 8</td>
<td>6 ± 3</td>
<td>6 ± 4</td>
<td>12 ± 3</td>
<td>12 ± 4</td>
</tr>
<tr>
<td>459.205</td>
<td>Cr II</td>
<td>12 ± 11</td>
<td>10 ± 8</td>
<td>−5 ± 5</td>
<td>13 ± 4</td>
<td>29 ± 6</td>
</tr>
<tr>
<td>461.881</td>
<td>Cr II</td>
<td>−8 ± 7</td>
<td>17 ± 4</td>
<td>2 ± 3</td>
<td>12 ± 3</td>
<td>−1 ± 5</td>
</tr>
<tr>
<td>462.933</td>
<td>Fe II</td>
<td>2 ± 4</td>
<td>11 ± 3</td>
<td>6 ± 2</td>
<td>7 ± 2</td>
<td>4 ± 3</td>
</tr>
<tr>
<td>467.041</td>
<td>Sc II</td>
<td>−20 ± 7</td>
<td>14 ± 9</td>
<td>−4 ± 4</td>
<td>18 ± 4</td>
<td>37 ± 4</td>
</tr>
<tr>
<td>473.144</td>
<td>Fe II</td>
<td>−19 ± 6</td>
<td>13 ± 5</td>
<td>2 ± 3</td>
<td>10 ± 3</td>
<td>7 ± 4</td>
</tr>
<tr>
<td>480.509</td>
<td>Ti II</td>
<td>−12 ± 4</td>
<td>16 ± 5</td>
<td>−4 ± 2</td>
<td>10 ± 2</td>
<td>18 ± 3</td>
</tr>
<tr>
<td>486.135</td>
<td>H I</td>
<td>46 ± 23</td>
<td>89 ± 5</td>
<td>85 ± 7</td>
<td>74 ± 3</td>
<td>101 ± 4</td>
</tr>
<tr>
<td>492.392</td>
<td>Fe II</td>
<td>8 ± 4</td>
<td>14 ± 2</td>
<td>8 ± 3</td>
<td>6 ± 2</td>
<td>−1 ± 3</td>
</tr>
<tr>
<td>493.408</td>
<td>Ba II</td>
<td>149 ± 6</td>
<td>−16 ± 3</td>
<td>...</td>
<td>42 ± 4</td>
<td></td>
</tr>
<tr>
<td>495.760</td>
<td>Fe I</td>
<td>140 ± 6</td>
<td>...</td>
<td>−10 ± 4</td>
<td>...</td>
<td>37 ± 4</td>
</tr>
<tr>
<td>501.844</td>
<td>Fe II</td>
<td>−1 ± 4</td>
<td>16 ± 2</td>
<td>14 ± 3</td>
<td>10 ± 2</td>
<td>−1 ± 3</td>
</tr>
<tr>
<td>512.916</td>
<td>Ti II</td>
<td>−9 ± 9</td>
<td>7 ± 4</td>
<td>0 ± 3</td>
<td>6 ± 3</td>
<td>26 ± 4</td>
</tr>
<tr>
<td>516.732</td>
<td>Mg I</td>
<td>146 ± 8</td>
<td>2 ± 8</td>
<td>−4 ± 3</td>
<td>18 ± 5</td>
<td>35 ± 5</td>
</tr>
<tr>
<td>516.890</td>
<td>Mg I</td>
<td>148 ± 6</td>
<td>2 ± 8</td>
<td>−4 ± 3</td>
<td>17 ± 5</td>
<td>35 ± 5</td>
</tr>
<tr>
<td>516.903</td>
<td>Fe II</td>
<td>4 ± 4</td>
<td>17 ± 3</td>
<td>13 ± 3</td>
<td>13 ± 2</td>
<td>−4 ± 3</td>
</tr>
<tr>
<td>517.268</td>
<td>Mg I</td>
<td>−8 ± 5</td>
<td>22 ± 5</td>
<td>1 ± 3</td>
<td>10 ± 4</td>
<td>24 ± 7</td>
</tr>
<tr>
<td>518.360</td>
<td>Mg I</td>
<td>−9 ± 4</td>
<td>12 ± 4</td>
<td>−2 ± 3</td>
<td>16 ± 2</td>
<td>25 ± 3</td>
</tr>
<tr>
<td>519.757</td>
<td>Fe II</td>
<td>−1 ± 4</td>
<td>16 ± 3</td>
<td>7 ± 3</td>
<td>7 ± 2</td>
<td>−3 ± 3</td>
</tr>
<tr>
<td>523.732</td>
<td>Cr II</td>
<td>2 ± 7</td>
<td>8 ± 4</td>
<td>−2 ± 3</td>
<td>11 ± 3</td>
<td>17 ± 3</td>
</tr>
</tbody>
</table>

Continued on Next Page...
Table 4.5 – Continued

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Species</th>
<th>20060208 PA (deg)</th>
<th>20080825 PA (deg)</th>
<th>20081018 PA (deg)</th>
<th>20081207a PA (deg)</th>
<th>20080213b PA (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>527.600</td>
<td>Fe II</td>
<td>4 ± 4</td>
<td>15 ± 3</td>
<td>5 ± 3</td>
<td>9 ± 2</td>
<td>4 ± 4</td>
</tr>
<tr>
<td>531.678</td>
<td>Fe II</td>
<td>-1 ± 4</td>
<td>18 ± 3</td>
<td>10 ± 3</td>
<td>10 ± 2</td>
<td>4 ± 4</td>
</tr>
<tr>
<td>536.275</td>
<td>Fe II</td>
<td>-1 ± 3</td>
<td>7 ± 2</td>
<td>2 ± 3</td>
<td>5 ± 2</td>
<td>5 ± 3</td>
</tr>
<tr>
<td>552.679</td>
<td>Sc II</td>
<td>-21 ± 5</td>
<td>7 ± 5</td>
<td>-5 ± 3</td>
<td>14 ± 3</td>
<td>25 ± 4</td>
</tr>
<tr>
<td>645.638</td>
<td>Fe II</td>
<td>-7 ± 4</td>
<td>8 ± 3</td>
<td>1 ± 3</td>
<td>8 ± 2</td>
<td>9 ± 3</td>
</tr>
<tr>
<td>656.280</td>
<td>H I</td>
<td>96 ± 2</td>
<td>110 ± 1</td>
<td>112 ± 1</td>
<td>115 ± 1</td>
<td>121 ± 1</td>
</tr>
<tr>
<td>771.149</td>
<td>O I</td>
<td>-11 ± 4</td>
<td>19 ± 5</td>
<td>-6 ± 4</td>
<td>43 ± 4</td>
<td>57 ± 2</td>
</tr>
</tbody>
</table>

Note: These data are polarization position angles for the line core calculated from error–weighted Stokes Q and error–weighted Stokes U, where the line core is defined as the line rest wavelength ± 25 km s\(^{-1}\) and the data have been rotated into the stellar frame of reference and corrected for stellar motion (see text).


\(^c\)Blend; not a significant contributor to polarization.

\(^d\)Blend; may contribute to polarization.
<table>
<thead>
<tr>
<th>Spec</th>
<th>Wavel (nm)</th>
<th>Lower level</th>
<th>Term</th>
<th>J&lt;sub&gt;i&lt;/sub&gt;</th>
<th>Conf</th>
<th>Term</th>
<th>J&lt;sub&gt;k&lt;/sub&gt;</th>
<th>E&lt;sub&gt;i&lt;/sub&gt; (eV)</th>
<th>E&lt;sub&gt;k&lt;/sub&gt; (eV)</th>
<th>A&lt;sub&gt;ki&lt;/sub&gt; (s&lt;sup&gt;-1&lt;/sup&gt;)</th>
<th>f&lt;sub&gt;ik&lt;/sub&gt;</th>
<th>log(gf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H I</td>
<td>410.173</td>
<td>2</td>
<td>6</td>
<td>10.20</td>
<td>13.22</td>
<td>9.73E+05</td>
<td>2.21E-02</td>
<td>-0.75</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>434.047</td>
<td>2</td>
<td>5</td>
<td>10.20</td>
<td>13.05</td>
<td>2.53E+06</td>
<td>4.47E-02</td>
<td>-0.45</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>486.135</td>
<td>2</td>
<td>4</td>
<td>10.20</td>
<td>12.75</td>
<td>8.42E+06</td>
<td>1.19E-01</td>
<td>-0.02</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>656.280</td>
<td>2</td>
<td>3</td>
<td>10.20</td>
<td>12.09</td>
<td>4.41E+07</td>
<td>6.41E-01</td>
<td>0.71</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O I</td>
<td>777.194</td>
<td>2s2.2p3.(4S*).3s</td>
<td>5S*</td>
<td>2</td>
<td>2s2.2p3.(4S*).3p</td>
<td>5P</td>
<td>3</td>
<td>9.15</td>
<td>10.74</td>
<td>3.69E+07</td>
<td>4.68E-01</td>
<td>0.37</td>
</tr>
<tr>
<td></td>
<td>517.732</td>
<td>3s.3p</td>
<td>3P*</td>
<td>0</td>
<td>3s.4s</td>
<td>3S</td>
<td>1</td>
<td>2.71</td>
<td>5.11</td>
<td>1.13E+07</td>
<td>1.35E-01</td>
<td>-0.87</td>
</tr>
<tr>
<td></td>
<td>518.360</td>
<td>3s.3p</td>
<td>3P*</td>
<td>1</td>
<td>3s.4s</td>
<td>3S</td>
<td>1</td>
<td>2.71</td>
<td>5.11</td>
<td>3.37E+07</td>
<td>1.35E-01</td>
<td>-0.39</td>
</tr>
<tr>
<td></td>
<td>656.280</td>
<td>3s.3p</td>
<td>3P*</td>
<td>2</td>
<td>3s.4s</td>
<td>3S</td>
<td>1</td>
<td>2.72</td>
<td>5.11</td>
<td>5.61E+07</td>
<td>1.36E-01</td>
<td>-0.17</td>
</tr>
<tr>
<td>K I</td>
<td>769.896</td>
<td>3p6.4s</td>
<td>2S</td>
<td>1/2</td>
<td>3p6.4p</td>
<td>2P*</td>
<td>1/2</td>
<td>0.00</td>
<td>1.61</td>
<td>3.75E+07</td>
<td>3.33E-01</td>
<td>-0.176</td>
</tr>
<tr>
<td></td>
<td>422.673</td>
<td>3p6.4s2</td>
<td>1S</td>
<td>0</td>
<td>3p6.4s.4p</td>
<td>1D*</td>
<td>1</td>
<td>0.00</td>
<td>2.93</td>
<td>2.18E+08</td>
<td>1.75E+00</td>
<td>0.24</td>
</tr>
<tr>
<td></td>
<td>467.041</td>
<td>3p6.3d2</td>
<td>1D</td>
<td>2</td>
<td>3p6.3d.4p</td>
<td>1F*</td>
<td>3</td>
<td>1.36</td>
<td>4.01</td>
<td>1.16E+07</td>
<td>5.30E-02</td>
<td>-0.58</td>
</tr>
<tr>
<td></td>
<td>552.679</td>
<td>3p6.3d2</td>
<td>1G</td>
<td>4</td>
<td>3p6.3d.4p</td>
<td>1F*</td>
<td>3</td>
<td>1.77</td>
<td>4.01</td>
<td>3.30E+07</td>
<td>1.18E-01</td>
<td>0.02</td>
</tr>
<tr>
<td>Ti II</td>
<td>422.733</td>
<td>3d3</td>
<td>a 2G</td>
<td>9/2</td>
<td>3d2.(3F).4p</td>
<td>z 4D*</td>
<td>7/2</td>
<td>1.13</td>
<td>4.06</td>
<td>2.71E+05</td>
<td>5.81E-04</td>
<td>-2.236</td>
</tr>
<tr>
<td></td>
<td>444.380</td>
<td>3d2.(1D).4s</td>
<td>a 2D</td>
<td>3/2</td>
<td>3d2.(3F).4p</td>
<td>z 2F*</td>
<td>5/2</td>
<td>1.08</td>
<td>3.87</td>
<td>1.08E+07</td>
<td>4.80E-02</td>
<td>-0.72</td>
</tr>
<tr>
<td></td>
<td>444.555</td>
<td>3d3</td>
<td>a 2G</td>
<td>7/2</td>
<td>3d2.(3F).4p</td>
<td>z 2F*</td>
<td>7/2</td>
<td>1.12</td>
<td>3.90</td>
<td>3.90E+05</td>
<td>0.001</td>
<td>-2.03</td>
</tr>
<tr>
<td></td>
<td>446.849</td>
<td>3d3</td>
<td>a 2G</td>
<td>9/2</td>
<td>3d2.(3F).4p</td>
<td>z 2F*</td>
<td>7/2</td>
<td>1.13</td>
<td>3.90</td>
<td>1.00E+07</td>
<td>2.40E-02</td>
<td>-0.62</td>
</tr>
<tr>
<td></td>
<td>450.127</td>
<td>3d3</td>
<td>a 2G</td>
<td>7/2</td>
<td>3d2.(3F).4p</td>
<td>z 2F*</td>
<td>5/2</td>
<td>1.12</td>
<td>3.87</td>
<td>9.37E+06</td>
<td>2.14E-02</td>
<td>-0.77</td>
</tr>
<tr>
<td></td>
<td>453.389</td>
<td>3d3</td>
<td>a 2P</td>
<td>3/2</td>
<td>3d2.(3F).4p</td>
<td>z 2D*</td>
<td>5/2</td>
<td>1.24</td>
<td>3.97</td>
<td>9.20E+06</td>
<td>4.30E-02</td>
<td>-0.77</td>
</tr>
<tr>
<td></td>
<td>455.387</td>
<td>3d3</td>
<td>a 2P</td>
<td>1/2</td>
<td>3d2.(3F).4p</td>
<td>z 2D*</td>
<td>3/2</td>
<td>1.22</td>
<td>3.94</td>
<td>8.80E+06</td>
<td>5.50E-02</td>
<td>-0.96</td>
</tr>
<tr>
<td></td>
<td>462.929</td>
<td>3d3</td>
<td>a 4P</td>
<td>5/2</td>
<td>3d2.(3F).4p</td>
<td>z 4F*</td>
<td>7/2</td>
<td>1.18</td>
<td>3.86</td>
<td>2.20E+05</td>
<td>9.40E-04</td>
<td>-2.25</td>
</tr>
<tr>
<td></td>
<td>480.509</td>
<td>3d2.(3P).4s</td>
<td>b 2P</td>
<td>3/2</td>
<td>3d2.(3P).4p</td>
<td>z 2S*</td>
<td>1/2</td>
<td>2.06</td>
<td>4.64</td>
<td>1.10E+07</td>
<td>1.90E-02</td>
<td>-1.12</td>
</tr>
<tr>
<td></td>
<td>512.916</td>
<td>3d2.(1G).4s</td>
<td>b 2G</td>
<td>9/2</td>
<td>3d2.(3F).4p</td>
<td>z 2G*</td>
<td>9/2</td>
<td>1.89</td>
<td>4.31</td>
<td>1.46E+06</td>
<td>5.76E-03</td>
<td>-1.24</td>
</tr>
<tr>
<td>Cr II</td>
<td>458.820</td>
<td>3d5</td>
<td>b 4F</td>
<td>7/2</td>
<td>3d4.(5D).4p</td>
<td>z 4D*</td>
<td>5/2</td>
<td>4.07</td>
<td>6.77</td>
<td>1.20E+07</td>
<td>2.80E-02</td>
<td>-0.64</td>
</tr>
<tr>
<td></td>
<td>459.205</td>
<td>3d5</td>
<td>b 4F</td>
<td>5/2</td>
<td>3d4.(5D).4p</td>
<td>z 4D*</td>
<td>5/2</td>
<td>4.07</td>
<td>6.77</td>
<td>3.20E+06</td>
<td>1.00E-02</td>
<td>-1.22</td>
</tr>
<tr>
<td></td>
<td>461.881</td>
<td>3d5</td>
<td>b 4F</td>
<td>5/2</td>
<td>3d4.(5D).4p</td>
<td>z 4D*</td>
<td>3/2</td>
<td>4.07</td>
<td>6.76</td>
<td>6.10E+06</td>
<td>1.30E-02</td>
<td>-1.11</td>
</tr>
<tr>
<td></td>
<td>523.732</td>
<td>3d5</td>
<td>b 4F</td>
<td>9/2</td>
<td>3d4.(5D).4p</td>
<td>z 4F*</td>
<td>9/2</td>
<td>4.07</td>
<td>6.44</td>
<td>1.70E+06</td>
<td>7.00E-03</td>
<td>-1.16</td>
</tr>
<tr>
<td>Fe I</td>
<td>461.876</td>
<td>3d6.4s2</td>
<td>b 3G</td>
<td>5</td>
<td>3d6.(3H).4s.4p.(3P*)</td>
<td>y 3G*</td>
<td>4</td>
<td>2.95</td>
<td>5.63</td>
<td>1.36E+05</td>
<td>3.56E-04</td>
<td>-2.41</td>
</tr>
<tr>
<td></td>
<td>495.750</td>
<td>3d6.(5D).4s.4p.(3P*)</td>
<td>z 7F*</td>
<td>4</td>
<td>3d6.(5D).4s.(6D).5s</td>
<td>e 7D</td>
<td>4</td>
<td>2.85</td>
<td>5.35</td>
<td>1.18E+07</td>
<td>4.34E-02</td>
<td>-0.41</td>
</tr>
</tbody>
</table>

Continued on Next Page...
Table 4.6 – Continued

<table>
<thead>
<tr>
<th>Spec</th>
<th>Wavel Conf Term</th>
<th>Lower level SF</th>
<th>Term</th>
<th>J_i</th>
<th>Conf</th>
<th>Term</th>
<th>J_k</th>
<th>E_i (eV)</th>
<th>E_k (eV)</th>
<th>A_{ik} (s^{-1})</th>
<th>f_{ik}</th>
<th>log(gf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>516.890</td>
<td>3d6.4s2 a 5D</td>
<td>3</td>
<td>3d6.(5D).4s.4p.(3P*)</td>
<td>z 7D*</td>
<td>3</td>
<td>0.05</td>
<td>2.45</td>
<td>3.83E+03</td>
<td>1.53E-05</td>
<td>-3.97</td>
<td></td>
<td></td>
</tr>
<tr>
<td>516.930</td>
<td>3d8 c 3F</td>
<td>4</td>
<td>3d7.(2D2).4p</td>
<td>t 3D*</td>
<td>3</td>
<td>4.08</td>
<td>6.47</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe II</td>
<td>423.316</td>
<td>3d6.(3P2).4s b 4P</td>
<td>5/2</td>
<td>3d6.(5D).4p</td>
<td>z 4D*</td>
<td>7/2</td>
<td>2.58</td>
<td>5.51</td>
<td>7.20E+05</td>
<td>2.60E-03</td>
<td>-1.81</td>
<td></td>
</tr>
<tr>
<td>438.538</td>
<td>3d6.(3P2).4s b 4P</td>
<td>1/2</td>
<td>3d6.(5D).4p</td>
<td>z 4D*</td>
<td>1/2</td>
<td>2.78</td>
<td>5.60</td>
<td>4.50E+05</td>
<td>1.30E-03</td>
<td>-2.60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>450.828</td>
<td>3d6.(3F2).4s b 4F</td>
<td>3/2</td>
<td>3d6.(5D).4p</td>
<td>z 4D*</td>
<td>1/2</td>
<td>2.86</td>
<td>5.60</td>
<td>7.00E+05</td>
<td>1.10E-03</td>
<td>-2.30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>451.533</td>
<td>3d6.(3F2).4s b 4F</td>
<td>5/2</td>
<td>3d6.(5D).4p</td>
<td>z 4F*</td>
<td>5/2</td>
<td>2.84</td>
<td>5.59</td>
<td>2.40E+05</td>
<td>7.20E-04</td>
<td>-2.36</td>
<td></td>
<td></td>
</tr>
<tr>
<td>452.022</td>
<td>3d6.(3F2).4s b 4F</td>
<td>9/2</td>
<td>3d6.(5D).4p</td>
<td>z 4F*</td>
<td>7/2</td>
<td>2.81</td>
<td>5.55</td>
<td>1.00E+05</td>
<td>2.40E-04</td>
<td>-2.60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>452.263</td>
<td>3d6.(3F2).4s b 4F</td>
<td>5/2</td>
<td>3d6.(5D).4p</td>
<td>z 4D*</td>
<td>3/2</td>
<td>2.84</td>
<td>5.58</td>
<td>8.40E+05</td>
<td>1.70E-03</td>
<td>-1.99</td>
<td></td>
<td></td>
</tr>
<tr>
<td>462.933</td>
<td>3d6.(3F2).4s b 4F</td>
<td>9/2</td>
<td>3d6.(5D).4p</td>
<td>z 4F*</td>
<td>9/2</td>
<td>2.81</td>
<td>5.48</td>
<td>1.70E+05</td>
<td>5.50E-04</td>
<td>-2.26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>473.144</td>
<td>3d5.4s2 a 6S</td>
<td>5/2</td>
<td>3d6.(5D).4p</td>
<td>z 4D*</td>
<td>7/2</td>
<td>2.89</td>
<td>5.51</td>
<td>2.80E+04</td>
<td>1.20E-04</td>
<td>-3.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>492.392</td>
<td>3d5.4s2 a 6S</td>
<td>5/2</td>
<td>3d6.(5D).4p</td>
<td>z 6P*</td>
<td>3/2</td>
<td>2.89</td>
<td>5.41</td>
<td>4.30E+06</td>
<td>1.04E-02</td>
<td>-1.21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>501.844</td>
<td>3d5.4s2 a 6S</td>
<td>5/2</td>
<td>3d6.(5D).4p</td>
<td>z 6P*</td>
<td>5/2</td>
<td>2.89</td>
<td>5.36</td>
<td>2.00E+06</td>
<td>7.50E-03</td>
<td>-1.35</td>
<td></td>
<td></td>
</tr>
<tr>
<td>516.903</td>
<td>3d5.4s2 a 6S</td>
<td>5/2</td>
<td>3d6.(5D).4p</td>
<td>z 6P*</td>
<td>7/2</td>
<td>2.89</td>
<td>5.29</td>
<td>4.20E+06</td>
<td>2.30E-02</td>
<td>-0.87</td>
<td></td>
<td></td>
</tr>
<tr>
<td>519.757</td>
<td>3d6.(3G).4s a 4G</td>
<td>5/2</td>
<td>3d6.(5D).4p</td>
<td>z 4F*</td>
<td>3/2</td>
<td>3.23</td>
<td>5.62</td>
<td>5.50E+05</td>
<td>1.50E-03</td>
<td>-2.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>527.600</td>
<td>3d6.(3G).4s a 4G</td>
<td>9/2</td>
<td>3d6.(5D).4p</td>
<td>z 4F*</td>
<td>7/2</td>
<td>3.20</td>
<td>5.55</td>
<td>3.80E+05</td>
<td>1.30E-03</td>
<td>-1.90</td>
<td></td>
<td></td>
</tr>
<tr>
<td>531.678</td>
<td>3d6.(3G).4s a 4G</td>
<td>7/2</td>
<td>3d6.(5D).4p</td>
<td>z 4D*</td>
<td>5/2</td>
<td>3.22</td>
<td>5.55</td>
<td>6.00E+04</td>
<td>2.10E-04</td>
<td>-2.80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>536.275</td>
<td>3d6.(5D).4d e 6G</td>
<td>7/2</td>
<td>3d6.(5D&lt;3&gt;+.4f</td>
<td>2[5]*</td>
<td>9/2</td>
<td>10.50</td>
<td>12.81</td>
<td>1.50E+07</td>
<td>8.10E-02</td>
<td>-0.19</td>
<td></td>
<td></td>
</tr>
<tr>
<td>645.638</td>
<td>3d6.(3D).4s b 4D</td>
<td>7/2</td>
<td>3d6.(5D).4p</td>
<td>z 4P*</td>
<td>5/2</td>
<td>3.90</td>
<td>5.82</td>
<td>1.70E+05</td>
<td>8.00E-04</td>
<td>-2.20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>656.220</td>
<td>3d6.(5D).4p z 4D*</td>
<td>1/2</td>
<td>3d5.4s2</td>
<td>c 4D</td>
<td>3/2</td>
<td>5.60</td>
<td>7.49</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ba II</td>
<td>493.408</td>
<td>6s 2S</td>
<td>1/2</td>
<td>6p</td>
<td>2P*</td>
<td>1/2</td>
<td>0.00</td>
<td>2.51</td>
<td>9.53E+07</td>
<td>3.48E-01</td>
<td>-0.16</td>
<td></td>
</tr>
</tbody>
</table>

Note: This table contains NIST data for the atomic transitions that contribute to significant (% > 4σ) polarization. The spectrum, laboratory wavelength, and the lower and upper configuration, terms and J value of the transition are given as well as the energies, Einstein coefficient for spontaneous emission, the oscillator strength and log(gf). An asterisk indicates odd parity.
Figure 4.1: Fe II (501.844 nm) and Mg II (517.268 nm) line variability. Strong line of Fe II (501.844 nm) (left) and medium strength line Mg I (517.268 nm) (right) with the out–of–eclipse data over–plotted to illustrate line variability. The line color corresponds to 2006–02–08 (red); 2008–08–25 (green); 2008–10–18 (blue); 2008–12–07, 2008–12–08, 2008–12–09, 2008–12–10, 2008–12–16 (dark violet); 2009–02–13, 2009–02–14, 2009–02–17 (brown). Spectra have been corrected for stellar radial velocity using the ephemeris of Stefanik et al. (2010). Note the line core is sometimes shifted from the line rest wavelength.
Figure 4.2: The Fe II (450.827 nm) line corrected for stellar and systemic radial velocity using the ephemeris of Stefanik et al. (2010) (left). The same spectral feature corrected for motion of a binary companion of equal mass (right). Note the line is centered at the rest wavelength (plotted in velocity scale) when corrected for the F0 star motion, but not when corrected for a binary companion of equal mass. All absorption features observed in ε Aurigae spectra are attributed to the F0 star (classified as a single–line spectroscopic binary). Significant (> 4σ) polarization (blue diamond) and (> 3σ) polarization (green asterisk) peaks are indicated. Polarization consistently corresponds to the line core absorption (0 km s⁻¹ ± 25 km s⁻¹) in ESPaDOnS observations.
Figure 4.3: Left (top): K i (769.896 nm) line 2006–02–08 (black) divided by an epoch–binned average ESPaDOnS observation of the same line (red). The data are wavelength–binned (bin size 0.008 nm). The average spectrum represents the unchanging interstellar absorption component. The velocity zero point is the K i (769.896 nm) line rest wavelength; the data have not been adjusted for stellar velocity. The resulting ratioed spectrum (bottom) reveals a broad weak absorption. The dotted line marks the normalized continuum. The star symbol marks the radial velocity of the F0 star. Dashed line is a Gaussian fit to the absorption feature. Right: symbols same as the left figure for a later observation 2009–02–17; notice the Gaussian centroid has shifted blueward along with the F0 star RV.
Figure 4.4: Position angles associated with significant ($\geq 4\sigma$) polarization peaks in out–of–eclipse data, plotted by the wavelength of the observed peak. The data are binned (bin size 0.008 nm) and are rotated into the stellar frame of reference. Most polarization peaks have position angles near 0° (low angles), but a few transitions such as H$\alpha$ (H i 656.280 nm) have position angles near 90° (high angles). Average line core position angles are presented in Table 4.5. Note the variability in the number of peaks and their position angles by epoch. We observe very little polarization in 2006–02–08 and 2009–02–13 (Table 4.4).
Figure 4.5: Ti\textsc{ii} (512.916 nm) medium–strength $s - p$ transition polarized flux (left) and $\%p$ (right). Significant (> 4$\sigma$) polarization (blue diamond) and (> 3$\sigma$) polarization (green asterisk) $\%p$ peaks are indicated (right). The polarized flux for this line varies from 0.17±0.01 mA above the continuum (2006–02–08) to 1.43±0.01 mA above the continuum (2008–10–18), shown here. This degree of variability is observed in other lines. The line absorption varies from 282 ± 1 mA (2008–08–25, 2008–12–07) to 338 ± 1 mA (2006–02–08). The amount of polarized flux is not always well–correlated with line strength.
Figure 4.6: Hα line profile (above) and linear polarization, %p, (bottom) from the 2008–12–07 spectrum. Hα line core polarization is present in all out-of-eclipse ESPaDOnS spectra. The polarization is slightly blue-shifted with respect to the line rest wavelength in this observation. The polarization data are binned (bin size 0.008 nm) and are rotated into the stellar frame of reference (see text). The linear polarization has been bias-corrected. Significant (> 4σ) polarization (blue diamond) and (> 3σ) polarization (green asterisk) peaks are indicated. The polarization feature at about −40 km s⁻¹ corresponds to the transition Fe II (656.220 nm; $E_U = 5.60$ eV) which is obscured by the broad Hα absorption feature. The other lines of this ionized iron multiplet are seen in absorption (unpolarized) elsewhere in the spectrum. Spectropolarimetry is a useful tool for line identification. In this case, an unpolarized line at these wavelengths would not have been identified because of the wide Hα wings.
Figure 4.7: Hα position angles for the observation 2008–12–07. The line profile and linear polarization for this epoch are plotted in Figure 4.6. The line core is defined as \(0 \pm 25 \text{ km s}^{-1}\) (green asterisk), the blue wing \((-125 \text{ km s}^{-1}\) to \(-25 \text{ km s}^{-1}\); blue asterisk) and red wing \((25 \text{ km s}^{-1}\) to \(125 \text{ km s}^{-1}\); red asterisk) are also used to estimate the error–weighted average position angles listed. The position angle of the Hα line core polarization is consistently at angles greater than 90° in out–of–eclipse observations (Table 4.5).
Figure 4.8: Hα line profile (above) and linear polarization, %p, (bottom) from the 2006–02–08 spectrum. Symbols as in Figure 4.6. An unusual blue–shifted absorption is observed in Hα for a few months in late 2005 and early 2006 (see text). An epoch–binned intensity observation (2008–12–07 through 2008–12–16, Table 4.1) is plotted for comparison (dashed line). The polarization peaks associated with the blue–shifted absorption are less pronounced than the line core polarization peaks, even though the absorption is deeper. The position angles also differ greatly (Fig 4.9).
Figure 4.9: Hα position angles for the observation 2006–02–08, an epoch with an unusual intensity profile. The line profile and linear polarization for this epoch are plotted in Figure 4.8. Symbols as in Fig 4.7. The line core position angle averages near 90°, while the wings are polarized at low angles near 0°. A position angle of 90° could arise from multiple scattering in optically thick material. Also note the drift in PA across the line core, corresponding to a loop in QU–space (Fig 4.10). This may be an indication of bulk motion in material contributing to the line core polarization. Compare this PA signature to Fig 4.7, for example.
Figure 4.10: QU-plots of Hα linear polarization for the observations 2006–02–08 (left) and 2008–12–07 (right), for comparison. Symbols as in Fig 4.7. Average uncertainty in Q and U lower right in each plot. Data are binned (bin size 0.008 nm) and have been rotated into the stellar frame (see text). The line core position angle corresponds to the excursions marked by green asterisks, while any blue wing polarization is noted by blue asterisks. Note the loop in the line core polarization evident in 2006 and the dramatic shift in position angles between the two observations.
Figure 4.11: H\textbeta{} (left) and H\textgamma{} (right) intensity profiles (top) and %p (bottom) observed on 2006–02–08 (solid line). An epoch–binned observation from 2008–12–07 is plotted for comparison (dashed line). Note the blue–shifted absorption present in the 2006 observations. Polarization data are binned (bin size 0.008 nm) and are rotated into the stellar frame of reference. The data have been corrected for stellar motion. These data are noisier than the H\alpha{} data (Fig. 4.10), but blue wing polarization peaks are present above the noise at 3\textsigma{} (H\beta{}) and 4\textsigma{} (H\gamma{}), pointing to some asymmetry in the outflow material.
Chapter 5

ESPaDOnS Spectropolarimetry of the $\varepsilon$ Aurigae system: the gaseous disk in scattered light

5.1 Summary

We seek to understand the evolutionary status of the disk by exploring the distribution of gas in the $\varepsilon$ Aurigae system. We evaluated spectral features and line polarization of select disk lines before, during and after eclipse in order to better resolve the distribution of gas in the disk. Disk rotation signatures appear in both low energy ($E_\text{ll} < 3$ eV) and high energy ($E_\text{ll} > 3$ eV) atomic transitions just after mid–eclipse even when additional absorption does not appear to be present in the line. Linear polarization ($\%p$) is bi–lobed and Stokes $U$ is antisymmetric through the line at these times. An increase in line polarization precedes an increase in continuum polarization near 3rd contact. We believe this is due to a density enhancement in the disk located on the side of the disk illuminated by the F0 star but offset from the direct line in the direction of disk rotation. We propose that scattering angles imposed by the system geometry are responsible for the phenomenon. Line polarization is stronger at egress than ingress supporting a model in which a temperature gradient is present in the disk, and the back side of the disk extends above the dusty opaque layer after mid–eclipse. We observe a polarization lag in lines with additional disk absorption features and in lines without additional disk absorption features. The observed antisymmetric Stokes $U$ profile across both types of line, similar to the effect produced by rotating optically thick gas disk models points to Rayleigh scattering as the polarization mechanism for both types of line.
5.2 Introduction

Otto Struve called $\varepsilon$ Aurigae, “In many respects the history of astrophysics since the beginning of the twentieth century” (Carroll et al., 1991). The eclipsing system has been observed by modern instruments in wavebands from the X–ray to the radio, and by visual observers for more than 100 years. Two possible models are presented for the system: the high-mass scenario (standard F0 supergiant) and the low mass (post–AGB) scenario (Guinan and Dewarf, 2002; Stencel, 2012). The ambiguity exists because the distance to the system is uncertain. The Hipparcos parallax is 1.53 ± 1.29 milliarcseconds, given by SIMBAD from van Leeuwen (2007). The work presented here adds to our understanding of the disk morphology and contributes to the discussion of the evolutionary status of the system.

The $\varepsilon$ Aurigae system consists of a bright ($V \sim 3$) variable F0Ia star ($\sim 7750$ K, log $g \sim 0$) and a BV star (15000 K, log $g \sim 4$) enshrouded in a dusty disk (Hoard et al., 2010, 2012). The system is irregularly variable with typical non–periodic $V$ band brightness variations of $\sim 0.1$ mag and an eclipse variation of 0.8 mag. The variability observed in the visible is more pronounced at shorter wavelengths, down to about 150 nm (Ake, 1985; Kemp et al., 1986). Low amplitude photometric variability at visible wavelengths is attributed to the F0 star. The opaque disk was imaged interferometrically in $H$–band during the most recent (2009–2011) eclipse and the disk transit was observed to be tilted from north toward east at $\sim 27^\circ$ (Kloppenborg et al., 2010). The orbital plane of the system is assumed to lie parallel to the direction of the observed transit. The rotation axis of the F0 star is perpendicular to the orbital plane of the system (Strassmeier et al., 2014).

*Based on observations obtained at the Canada-France-Hawaii Telescope (CFHT) which is operated by the National Research Council of Canada, the Institut National des Sciences de l’Univers of the Centre National de la Recherche Scientifique of France, and the University of Hawaii.
Spectral signatures of the disk are not seen in the visible spectra except during eclipse (single line binary system, SB1). Model atmospheres are difficult to fit to the F0 star spectrum because the F0 star envelope is extended and tenuous (surface gravity, log g \sim 0) and the outer stellar envelope is not well-described by local thermodynamic equilibrium (LTE) (e.g. Hack, 1959; Castelli, 1978; Chadima et al., 2011). In addition, radial velocity (RV) and equivalent width (EW) measurements of spectral absorption features are made difficult by the short-term variations in spectral lines both in- and out-of-eclipse.

An updated ephemeris is given by Stefanik et al. (2010). In this orbital solution, phase 0.0 corresponds to periastron and mid-eclipse occurs at phase \sim 0.09 (JD 2,455,413.8 \pm 4.8, 2010 August 5). The photometric eclipse begins near phase 0.056 (1\textsuperscript{st} contact) and ends near phase 0.130 (4\textsuperscript{th} contact), apastron is at phase 0.5 and secondary eclipse (never observed in the visible) occurs near phase \sim 0.6. The mass function is given by

\[
f(M_\odot) = \frac{(M_2 \sin i)^3}{(M_1 + M_2)^2}
\]

Here \(M_1\) is the mass of the primary (F0 star), \(M_2\) is the mass of the secondary, and \(i\) is the inclination. The eclipse is seen nearly edge-on, \(i = 89.55^\circ \pm 0.40^\circ\) (Kloppenborg, 2012). Stefanik et al. (2010) found \(f(M_\odot) = 2.51 \pm 0.12\).

The mass ratio, \(q\), is given by

\[
q = \frac{M_1}{M_2}
\]

5.2.1 Spectra

The F0 star features in the visible spectra are seen in absorption, except for H\(\alpha\) which has a persistent emission component. Disk lines in visible spectra are also seen in absorption during eclipse. Many disk lines are similar to those transitions
observed in F0 star spectra, with a few exceptions, and arise from low-excitation potential (E.P.) neutral and singly–ionized species. Weak transient disk features have been observed in visible spectra (e.g. Griffin and Stencel, 2013). In the infrared, a transient He I (10830 Å) emission has been observed during mid–eclipse (Stencel et al., 2011) and molecular CO absorption lines are seen only during late eclipse (Stencel et al., 2015).

During eclipse, the absorption spectrum of the gaseous component of the eclipsing body (the secondary) is seen in spectral features that are velocity–shifted with respect to the eclipsed body (the primary). The absorption lines are first observed to be red–shifted (ingress) and then blue–shifted (egress) because of the largely Keplerian rotation of the disk. Many authors have described the additional absorption features, or shell lines, attributed to disk during eclipse (e.g. Hack, 1959; Castelli, 1978; Lambert and Sawyer, 1986; Saito et al., 1987, and others). The opaque dusty disk has been described using a blackbody temperature of 550 ± 50 K (side facing away from the F0 star) and 1150 ± 50 K (side facing toward the F0 star) (Hoard et al., 2010, 2012). The secondary flux (attributed to dust emission) was directly detected at 5 µm, 10 µm and 20 µm (Backman et al., 1984).

5.2.2 Disk atmosphere

The distribution of material in the disk is asymmetric. Lines strengthen (exhibit greater EW and line depth) after mid–eclipse than before mid–eclipse (Lambert and Sawyer, 1986; Leadbeater and Stencel, 2010). Disk absorption lines are present in spectra after the end of photometric eclipse, suggesting the presence of trailing material (e.g. Ferluga and Mangiacapra, 1991). Other asymmetries include a ‘bump’ of
additional absorption, greater EW, and increased continuum polarization observed near 3rd contact (Kemp et al., 1986; Cole, 2012).

Gas is confined to a ring at the periphery of the opaque disk (e.g. Lambert and Sawyer, 1986). Griffin and Stencil (2013) observed narrow absorption lines that appeared only during early and late eclipse phases. They found that the disk was opaque except for optically thin material at its periphery which selectively absorbed the F0–star radiation behind it in the line of sight. They also discovered a very confined stream of material from the F0 star to the disk that is enriched in rare-earth elements (such as Nd II, Sm II, and others) evidenced by weak blue–shifted absorption features that were only visible for a short time around third contact between phases ~0.111 and 0.123, using the ephemeris of (Stefanik et al., 2010).

Some components of the gaseous envelope may be considerably larger than the opaque disk, both in scale height and in extent. Ferluga and Mangiacapra (1991) found that some strong lines were saturated in most eclipse phases, suggesting that the F0 star face was completely covered by gas along the line–of–sight during those phases. Similar behavior was also noted by Saito et al. (1987). Mourard et al. (2012) resolved Hα visibilities spectro–interferometrically and deduced that the F0 star was totally eclipsed in Hα (656.280 nm).

Strassmeier et al. (2014) identified 61 disk absorption lines sufficiently free of primary star contribution to characterize the rotational profile of the disk during eclipse. They fit radial velocity curves with a full orbital solution and categorized the lines as ‘high eccentricity’ and ‘low eccentricity’. They determined that transitions (line absorptions) with high excitation potential came from disk regions with higher eccentricity and higher rotational velocity. Many, but not all, transitions described
as low eccentricity came from lower rotational velocity regions. They deduced that transient absorption features in spectral lines with higher excitation potential (lower temperature sensitivity) originated from the outskirts of the disk or even the disk halo and not from the immediate vicinity of the hidden secondary.

5.2.3 Disk models

Several disk models have been proposed to explain photometric, line absorption and continuum polarization behavior of the system observed during eclipse. Lissauer et al. (1996) modeled light curves using quasi-hydrodynamic models of a geometrically thin circumstellar disk of gas and dust, which is rotationally supported about its short axis and pressure supported perpendicular to its midplane. These models suggested that absorption lines seen during and immediately after the F0 star eclipse are produced by a thin layer of gas in the outer portion of the disk. This gas expands when it is heated by radiation from the F0 star and contracts when it is shielded. Absorption line behaviors (deepest after the middle of the continuum eclipse and persisting after 4th contact), are reproduced by the Lissauer et al. models.

In these models, cold disk material rotates into the line–of–sight of the F star and is heated. The material does not reach maximum temperature until after the “noon” phase (disk material is directly between the F0 star and the B star at noon, Pearson and Stencel, 2015). Heated rotating material expands in the $z$ direction because the gas pressure increases. From Earth’s point of view, material on the back side of the disk expands above its midnight scale height beginning at 1st contact (disk dawn), increases through mid–eclipse (disk noon), and reaches its maximum near 3rd contact (disk mid–afternoon). The optically thin material above and below the optically thick disk may contribute to absorption in the line (increased EW) and
to scattering both in the continuum (via electron or dust scattering) and the line (via Rayleigh scattering from gas).

Lissauer et al. (1996) modeled the optical depth profile of the leading half of the disk in the sky plane for a quasi–hydrodynamic model that allowed for thermal expansion of the outer layer of the disk facing the primary star ($h = 0.03, i = 0.0^\circ$). They found that the scale height of the outermost 0.1% of the disk expanded linearly with time by a factor of 1.4 between dawn and the temperature maximum at mid–afternoon (not at noon); the scale height then contracted linearly until midnight.

Hoard et al. (2012) modeled an optically thin disk component as a corona or atmosphere of hotter dust grains extending 0.1 AU above and below the optically thick disk component (outer radius 3.8 AU, thickness 0.76 AU, at a distance of 625 pc) and with 1% of the mass estimated by Kloppenborg et al. (2010) for the optically thick disk component. The combined contribution of the two model components produced a total SED almost indistinguishable from a prior model (without an atmosphere; Hoard et al. (2010)). The authors found that the gas–to–dust ratio in the disk may be low because emission features were not observed from molecular species.

5.2.4 Polarization

The system shows out–of–eclipse (OOE) variations in brightness (e.g. Karlsson, 2012), as well as broadband (continuum) polarization (Coyne, 1972; Henson, 1989; Cole, 2012). The broadband polarization is largely interstellar, but a small, variable intrinsic component is also present. Both the degree and position angle of the observed polarization are variable on short ($\sim 100$ day) timescales (Henson, 1989).
Broadband polarization was observed during the prior (1982–1984) and most recent (2009–2011) eclipses (Kemp et al., 1986; Cole, 2012). The eclipse polarization shows modulation in both Stokes $Q$ and Stokes $U$ (observed north up on the plane of the sky). The eclipse polarization ($\% p$) exceeds the out–of–eclipse polarization by more than twice the measured $V$ band values (Cole, 2012, Fig. 1). Intrinsic continuum polarization may have contributions from more than one source in the system (see Chapter 6).

Line polarization is observed in– and out–of–eclipse for many atomic transitions seen in absorption (Geise et al., 2012). Harrington and Kuhn (2009) found roughly 1% linear polarization almost exactly at the H$\alpha$ line center in OOE ESPaDOnS observations 2006–02–07 & 2006–02–08. Many variable polarized spectral features were identified in 11 out–of–eclipse ESPaDOnS spectra spanning nearly 3 years of observations (Geise et al. 2015, in prep., hereafter Paper 1 (Chapter 4)). The line polarization observed out–of–eclipse is generally confined to the line core ($0 \pm 20$ km s$^{-1}$) and likely arises from an equatorial asymmetry in the extended atmosphere of the F0 star (Chapter 4). The report presented here addresses characteristics of line polarization observed during eclipse.

The present study is organized as follows: observations and reductions are described in section 5.3; results of spectral analysis in section 5.4; results of spectropolarimetric analysis in section 5.5; discussion in section 5.6; and conclusions and next steps in section 5.7.
5.3 Observations and reductions

5.3.1 Spectra and spectropolarimetry

High-resolution échelle spectropolarimetric data were obtained with the 3.6 m Canada–France–Hawaii optical/infrared telescope (CFHT) using the Échelle SpectroPolarimetric Device for the Observation of Stars (ESPaDOnS). More than 50 spectra of ε Aurigae were obtained over a 4 year period from pre–eclipse, through the nearly 2 year eclipse cycle (1\textsuperscript{st} contact, 2009 August 16) and up to 4 months after eclipse (4\textsuperscript{th} contact, 2011 August 26). Out–of–eclipse observations, including an earlier 2006 observation of ε Aurigae, were addressed in a separate analysis (see Chapter 4).

ESPaDOnS is a cross-dispersed échelle spectropolarimeter designed to obtain a complete optical spectrum (370 nm to 1,050 nm) in a single exposure, with a resolving power of ~65 000 (Donati, 2003; Donati et al., 2006). All 4 Stokes parameters were recorded for each observation (see Table 5.1 for a log of observations). ESPaDOnS data are archived as FITS files, with one file for each of the 3 Stokes parameters: \(Q\), \(U\), and \(V\). Total observed intensity, \(I\) (the 4\textsuperscript{th} Stokes parameter), is included in each file with wavelengths in nm. We made use of the fully–reduced, normalized data from each observation. We checked the included null parameters to be sure there was no spurious polarization in the data.

We retrieved ESPaDOnS observations of ε Aurigae from the Canadian Astronomy Data Centre (CADC)
\(^1\), Canada France Hawaii Telescope (CFHT) Science Data Archive. The data were automatically reduced with Upena, CFHTs reduction

\(^1\)Online http://www1.cadc-ccda.hia-iha.nrc-cnrc.gc.ca/cadc/
pipeline for ESPaDOnS. Upena uses Libre–ESpRIT, which is a proprietary data reduction software tool (Donati et al., 1997).

The ESPaDOnS data are noisier at shorter wavelengths (i.e. toward the blue) than longer wavelengths because the detector is less sensitive in the blue. We binned the linear polarization data with a wavelength bin of 0.008 nm using the error–weighted mean to boost signal–to–noise at shorter wavelengths and for deep absorption lines. In some cases, we combined several epochs (using the error–weighted mean) to further reduce noise using the criterion that the line profile did not change between binned epochs (typically a few days apart). We chose the bin size to ensure that there were no empty bins (except for the three very small gaps in the échelle spectrum) for the entire wavelength span of the observations. See Table 5.1 for the specific epochs used in binning.

5.3.2 Magnitudes

We retrieved eclipse magnitude data from the catalog of the American Association of Variable Star Observers (AAVSO)\(^2\). We averaged V band magnitudes over a 3–day window for each of the single ESPaDOnS observations and over the range of dates for epoch–binned observations. We plotted the calculated average against the high signal–to–noise AAVSO V band data for the recent eclipse in order to determine trends in the variability of the F0 star around each observation (see the discussion below).

5.3.3 Disk/stellar reference frame

The ε Aurigae system was imaged interferometrically by Kloppenborg et al. (2010) and the disk seen in eclipse was observed to be tilted with respect to north

\(^2\)Online at http://www.aavso.org
on the sky. Based on the imaging interferometry and as a first approximation to the
dominant geometry of the system, we assumed that the disk and orbital plane are
coplanar and the rotation axis of the F0 star is perpendicular to the orbital plane.
We assumed that scattering material in the system was likely to be distributed in
the orbital plane (or perpendicular to the plane, as in the case of polar jets). We
adopted a rotation angle of 27° to align north with the axis perpendicular to the
observed (inferred) orbital plane of the system. We rotated $Q$ and $U$ data using a
rotation matrix (e.g. Bagnulo et al., 2009) before calculating linear polarization and
position angles. Unless explicitly stated otherwise, all position angles in this study
were calculated using data rotated into the disk/stellar reference frame.

5.3.4 Linear polarization

The ESPaDOnS pipeline removes the continuum polarization, regardless of its
origin (instrumental, interstellar or circumstellar). We confirmed this assumption
by plotting largely interstellar lines such as the K $\lambda$ absorption feature and noting
that the scatter in the $QU$–plane was centered on (0,0). Featureless continuum
was also centered on (0,0) in the $QU$–plane. Any residual contribution from inter-
stellar polarization would shift the zero position to another point on the $Q,U$–plane.

We calculated linear polarization, $P$, using the ESPaDOnS $Q$ and $U$ Stokes pa-
rameters and the method described by Bagnulo et al. (2009), where
$P = \sqrt{Q^2 + U^2}/I$ and linear polarization is usually given as a percent, $\%p$. This formulation
yields a measure of scattered light as a percent of the total observed flux density.
We calculated polarized flux using $P = \%p * I/100 = \sqrt{Q^2 + U^2}$. We were
careful to correct Stokes $U$ by taking the negative of the archived value as described
in the FITS file header.
By definition, the parameter $P$ is a positive definite quantity. The individual polarization values calculated will always be positive and non–zero because the individual values of $Q$ and $U$ will generally be non–zero. When null, $Q$ and $U$ scatter around zero with uncertainty described by Poisson statistics, but linear polarization, $P$, is described by Rician statistics. We corrected for bias in $P$ (e.g. Simmons and Stewart, 1985) and we calculated average linear polarization using average Stokes $Q$ and $U$ (e.g. Clarke and Stewart, 1986). We observed no significant ($> 4\sigma$) Stokes V circular polarization in our ESPaDOnS data.

We employed direct integration of the line profile to calculate equivalent widths (EW) using unbinned ESPaDOnS data. We compared our results with published values whenever possible. We integrated polarized flux across the line using binned, calculated $P$ (bin size 0.008 nm) in order to compare the change to the scattered flux density over time. We analyzed changes to position angle (PA) separately.

We corrected for the positive bias in the integrated polarized flux by directly–integrating a featureless portion of the normalized continuum adjacent to the line and with the same width in wavelength. We did not account for a sloping continuum because ESPaDOnS spectra are flattened and normalized to 1 in the continuum. We then subtracted this integrated, but positive, null amount from the integrated polarized flux across the line. The resulting amount (line minus continuum) represents the polarized flux of intrinsic contributions observed in the line.

5.3.5 Line selection

We determined a global standard deviation for Stokes $Q$ and Stokes $U$ by creating a mask of featureless continuum for the range of wavelengths 400 nm to 900 nm. We identified polarization peaks that reached $\geq 4$ times the global Stokes $Q$ standard
deviation and where more than one peak was present in the line (fell within \( \sim 1 \) Å of a neighbor peak). These data were identified as “strong” polarization. Once the polarization signals exceeding the threshold value were identified, we plotted the spectral feature, classified each by the atomic transition and calculated the equivalent width of the spectral absorption feature and of the polarized flux as above. More than half of the lines also met our criteria for selection as strongly polarized in out-of-eclipse spectra (see Chapter 4).

We concentrated only on those spectral lines free of blends in the intensity spectrum, and with unambiguous classification and equivalent width measurement. Transition data for these strongly polarized eclipsed lines are listed in Table 5.6. See Chapter 4 (Table 4.6) for transition data for the lines also identified as strongly polarized out-of-eclipse. In the first eight columns of Table 5.6 we list the element, the laboratory wavelength, and the lower and upper configuration, terms and \( J \) value of the transition. The energies are listed in columns nine and ten. In column eleven we list the Einstein coefficients for spontaneous emission. In the last two columns we list the oscillator strength, \( f_{ik} \), and \( \log(gf) \).

Line polarization may arise from resonance scattering at atomic dipole transitions in the presence of some anisotropy. The polarization may occur in the line-forming region of an atmosphere if collisions are not dominant (non-LTE conditions); otherwise, the polarization may be associated with cooler, outer layers of an atmosphere, given some anisotropy.

5.3.6 Gas rotation

We calculated the line strength using out-of-eclipse spectra and the relationship strength \( = 1 - (f_{\text{line}}/f_{\text{continuum}}) \), assuming a normalized continuum of one
We defined a strong line as one that absorbed 40% or more of the normalized continuum flux in out–of–eclipse spectra ($f_{\text{line}} \leq 0.60$). We defined medium strength lines as absorbing 25% to 40% of the continuum ($0.75 \geq f_{\text{line}} > 0.60$). Weak lines absorbed less than 25% of the continuum ($f_{\text{line}} > 0.75$). Saturated lines, including the Na D lines at 588.995 nm and 589.590 nm, are not addressed in this work because the signal–to–noise is poor in the deepest part of the line.

We measured the central depth of the line ($f_{\text{line}}$) in all spectra by selecting the point of minimum flux within the range of wavelengths used to measure the equivalent width of the line. The central depth was offset from the line rest wavelength in most eclipse observations because of additional velocity–shifted disk absorption. We plotted the central depth in time series plots of Stokes $Q$, Stokes $U$ and $%p$ to determine epochs of changing polarization associated with disk absorption and to differentiate between disk and intrinsic F0 star polarization.

Assuming Keplerian rotation of the gas, slower–moving gas at the edges of the disk would contribute to the low velocities near the line core and faster–moving gas in the central part of the disk would contribute to the far wings. The velocity shift from rest of the central depth should then become more positive with the onset of eclipse and become less negative with waning eclipse as the rotating gas passes in front of the F0 star. We expect to find symmetry in the lines at mid–eclipse because the eclipsing objects should reach zero radial velocities around that time (regardless of the orbital solution used) and because the disk rotational velocities would be distributed equally along the line–of–sight, assuming a circularly symmetric disk.
5.4 Results and analysis: total flux spectra

5.4.1 Fe II (658.671 nm, 656.220 nm)

We discovered a previously unidentified line near Hα (656.280 nm) in out-of-eclipse spectra, Fe II 656.220 nm (Chapter 4, Fig. 4.6). The Fe II 656.220 nm line is only visible in polarization spectra because the intensity feature is hidden by the much stronger Hα absorption. We observed members of the same multiplet (z 4D* - c 4D) in order to confirm the presence of the polarization feature. Other lines of the multiplet are present in our spectra, but none are polarized. The multiplet lines are weak with transition energies from 5.6 eV to 7.5 eV. In this paper, we present another line from the multiplet, Fe II 658.671 nm.

We observe a weak transient absorption feature in the Fe II 658.671 nm line in spectra taken before and during eclipse. The feature is present in our pre-eclipse spectra dated from 2008–08–25 through 2008–12–16 corresponding to RJDs 54704, 54758, 54808, 54809, 54810, 54811, 54817 (Table 4.1). The feature, a small dimple in the unbinned intensity spectrum (about 1 pixel wide in data binned at 0.008 nm), moves from red to blue across the line. The feature is red-shifted in 2008–08–25 (RJD 54704), about line center at 2008–10–18 (RJD 5458) and progresses to the far blue wing by our spectrum 2009–02–13 (RJD 54876). The feature is not resolved in a spectrum dated 2009–02–14 (RJD 54877) but is visible in 2009–02–17 (RJD 54880).

The absorption lines are weak and the transition energies are high, therefore it is unlikely that the disk contributes to the absorption in the line. We observe the transient feature in the 658.671 nm line red-shifted in our early eclipse spectra 2009–09–25 (RJD 55100), much stronger in 2009–09–26 (Fig. 5.1) and weaker again in 2009–09–29 (RJD 55104). The feature is weakly present in several spectra and then
stronger and blue–shifted in 2009–12–02, 2009–12–04 & 2009–12–07 (RJDs 55168, 55170, 55173). The feature is not present in our spectrum 2010–01–02 (RJD 55199) and does not reappear until 2010–10–18 (RJD 55488) when it is again red–shifted. The transient is weakly observable until 2010–11–22 and 2010–11–24 (RJDs 55523, 55525) when it appears stronger at the 658.671 nm line rest wavelength. The feature is blue–shifted again by 2010–12–19 (RJD 55550). We do not observe the transient in our spectrum 2011–08–17 (RJD 55791), the next observation in the time series. It may be present and red–shifted in 2011–11–01 and 2011–11–16 (RJDs 55867, 55882) but is not resolved in our spectrum 2011–11–15 (RJD 55881). The feature is possibly present and blue–shifted in spectra dated 2012–01–06 and 2012–01–17 (RJDs 55933, 55944). It may be weakly present at line rest wavelength in our last observation dated 2012–12–09 (RJD 56271).

We believe the transient is a photospheric feature such as a large spot but observe that the motion is retrograde to the presumed rotation direction of the F0 star.

5.4.2 Disk spectral signatures

The disk rotation is seen in our ESPaDOnS spectra as radial–velocity shifted absorption. The spectral features that arise from disk gas absorption are first red–shifted and then blue–shifted when observed at line rest wavelengths, or when spectra are corrected for the F0 star orbital motion (which is small at near–eclipse epochs). The disk absorption radial velocity shifts are pronounced in most spectra, making decomposition of F0 star and disk contributions relatively easy, except for epochs when the low disk velocity material and the F0 star line core absorptions are superposed. Velocity–shifted spectral features were observed in prior eclipses and have been discussed by many observers (e.g. Lambert and Sawyer, 1986; Saito
et al., 1987; Ferluga and Mangiacapra, 1991). Our interest is in polarization features associated with disk absorption observed during eclipse.

5.5 Results and analysis: spectropolarimetry

More than 500 atomic transitions have been observed in absorption in $\varepsilon$ Aurigae spectra (e.g. Hack, 1959; Strassmeier et al., 2014). We identify 83 transitions (5 are blends) that exhibit significant ($>4\sigma$) polarization in our eclipse spectra. All of the polarized transitions observed out-of-eclipse (Chapter 4) also exhibit periods of significant polarization during eclipse. The atomic transitions are similar in both cases: the strongest polarization is observed in atomic transitions of singly-ionized iron and titanium in quantum-mechanically allowed transitions. We also observe polarization in atomic transitions of Sc II, Cr II, Fe I and Sr II during eclipse (Table 5.6).

The lines show the strongest polarization at and just after mid-eclipse in our observations, evidenced by an increase in polarized flux. The peak in polarization after mid-eclipse is present even in lines that do not show large additional disk absorption features (increased EW) during eclipse (discussion below).

5.5.1 1st contact to 2nd contact

Our time series provide the greatest eclipse coverage from 1st contact to 2nd contact. There are 18 observations over the roughly six months in the transition to totality (2009–08–16 to 2010–02–22). We epoch-binned these observations to reduce the noise in polarized flux and created a total of 5 epoch-binned observations for the period between 1st and 2nd contact. By 1st contact, many lines already display broadened lines and red-shifted absorption from rotating disk material. We observe a few lines with an increase in polarized flux EW (Table 5.4) in our epoch–
binned observation RJD 55086, about two weeks after 1st contact. Scattering from rotating disk material is evident in the polarization spectra for these lines (Fig. 5.3).

The Ca I 422.673 nm ground state transition and Hα (H I 656.280 nm) are two of the most strongly polarized transitions early in eclipse. For example, Hα shows evidence of disk rotation in 2009–09–04, our first observation after 1st contact. Stokes U (%u) is antisymmetric with a P-Cygni profile in this observation and those immediately following. Many lines show polarized flux EW above the OOE stellar variation by our final epoch–binned observation 2010–01–27, less than a month before 2nd contact (Table 5.4).

We observe three types of trend in equivalent width: lines whose EW increased after 1st contact, lines whose EW decreased after 1st contact and lines whose EW did not appear to change. Equivalent width increased in more than half the lines after 1st contact, with the remaining lines roughly divided between decreased EW or no/low change to EW (Table 5.2).

We checked the F0 star magnitude variability to be sure that changes to EW and polarized flux EW near 1st contact correlate with the eclipsing disk and not with F0 star behavior. The F0 star intrinsic brightness variations were well described by Karlsson (2012). During ingress, several minima and maxima may be observed even as the light curve decreases with the onset of eclipse (Karlsson, 2012, Fig. 4). We estimated the trends in the ingress curve using data from the AAVSO to determine if our ESPaDOnS observations occur during F0 star periods of maximum or minimum brightness (Fig. 5.2). We find our ESPaDOnS observations occur outside the
large amplitude variations near RJD 5160 (maximum) and RJD 5185 (minimum) noted by Karlsson.

Our first epoch–binned observation dated 2009–09–07 (binned RJDs 5079, 5080, 5083, 5086) coincides with an F0 star maximum identified by Karlsson (2012), but which was not present in our reduction of similar data. Our epoch–binned observations dated 2009–09–27 (RJDs 5100, 5101, 5104) and 2009–10–07 (RJDs 5107, 5112, 5115) may occur near an F0 star minimum at ∼RJD 5110 also identified by Karlsson (2012).

An increase in line absorption soon after 1st contact is unlikely to be related to any increase in F0 star brightness at that time and can be attributed to gas associated with the disk. Polarized flux EW is not above OOE F0 star variability soon after 1st contact for most lines. EW and polarized flux EW increase in many lines by 2nd contact, but the F0 star is not trending brighter or dimmer at that time. Changes to EW or polarized flux EW at 2nd contact are due to gas associated with the disk and not to F0 star variability.

5.5.2 Mid–eclipse to 3rd contact

Disk rotation is evident in line polarization for many atomic transitions observed near mid–eclipse. ESPaDOnS observations during eclipse agree with results obtained by radiative transfer models of rotating disks. For example, Milić and Faurobert (2014) modeled optically thick disks to identify possible polarimetric signatures arising from such disks. The non-LTE radiative transfer models included transitions by a two–level atom in a centrally– and self–irradiated, optically thick gaseous disks (τ_r = 10^3 and τ_r = 10^4). The authors suggested that antisymmetric
Stokes $U$, bi-lobed %$p$, and a rotation of position angle from positive to negative values could be indicators of disk rotation in these systems.

The atomic transition Fe II 531.66 nm ($E_U = 3.15$ eV, $A = 3.9 \times 10^5$ s$^{-1}$) is representative of many observed transitions with rotation signatures such as antisymmetric Stokes $U$ (a reverse P–Cygni profile after mid–eclipse), bi–lobed %$p$ and a position angle rotation through the line (Figs. 5.4 & 5.5). Disk rotation signatures are most pronounced in our observation 2010–10–18, about two months after mid–eclipse. Additional blue–shifted disk absorption is present in the line by this time (Fig. 5.4). Stokes $U$ is antisymmetric and the resulting polarization profile appears bi-lobed. The position angle rotates increasingly negative from blue toward the red with an apparent discontinuity at the line core because of our treatment of PA (Fig. 5.5).

5.5.3 Late eclipse

Our coverage is poor between 3$^{rd}$ contact and 4$^{th}$ contact with one observation, 2011–08–17 (RJD 55791, phase 0.129), about one week before 4$^{th}$ contact. There are several observations after 4$^{th}$ contact until our final observation 2012–12–09 (RJD 56271, phase 0.178). We observe little polarized flux above the noise after 3$^{rd}$ contact, although there may still be polarization (%$p > 4\sigma$), especially in the line cores of the strongest lines such as H$\alpha$. The narrow polarization peaks do not contribute substantially to the polarized flux in the line, which is measured across the entire absorption feature (Chapter 4). It is difficult to determine whether the source of the polarization is photospheric or disk–related after eclipse. For example, the line core of H$\alpha$ is slightly blue–shifted nearly six months after eclipse (2012–01–06) and the PA increases nearly linearly from 50$^\circ$ to 100$^\circ$ through the line core. However, the effect may be from F0 star atmospheric motion rather than disk rotation.
5.5.4 Spectral lines without disk absorption during eclipse

Atomic transitions have been identified that have F0 star photospheric absorption features but which appear to have no additional disk absorption during eclipse (e.g. Ferluga and Mangiacapra, 1991). Most recently, Strassmeier et al. (2014) identified 207 atomic transitions without disk absorption in échelle spectra covering visible wavelengths. We present detailed spectropolarimetric analysis of two transitions below.

Si II (634.710 nm). The Si II 634.710 nm line does not show large disk absorption or transient features during eclipse and the line profile variability appears semi–regular in a time series of spectra taken from 2006 through 2013 by the robotic telescopes STELLA (Strassmeier et al., 2014, Fig. 3a). The medium strength absorption line arises from a high energy ($E_{\text{ll}} > 3$ eV) transition ($E_{\text{ll}} = 8.12$ eV, $E_{\text{ul}} = 10.07$ eV). The equivalent width of the line does not change dramatically in our spectra during eclipse, although we observe small variations (Fig. 5.6). We observe an apparent increase in scattered light near 3rd contact without an apparent increase in absorption from disk material along the line–of–sight.

Two effects (in addition to underlying F0 star photospheric variability) contribute to the Si II 634.710 nm line profiles observed during eclipse. First, the line appears slightly red–shifted and then slightly blue–shifted in our spectra similar to lines with large disk absorption features. Second, the EW of the line appears anti–correlated with the polarized flux EW. For example, the line is variable in our out–of–eclipse spectra with an error–weighted average EW of 587 mA and a standard deviation of 13 mA (average of 11 observations). The line reaches a maximum equivalent width of 653 mA at 1st contact (uncertainty < 1 mA). The line falls to below its out–of–eclipse average EW after mid–eclipse beginning with the observa–
tion 2010–10–16 through 2010–11–17 (average EW 542 mA ± 11 mA). During this time, the line has the largest observed polarized flux EW. This is evidence that the photospheric absorption is contaminated by light scattered into the line–of–sight. The additional light contributes to the profile at this epoch to decrease the EW below its out–of–eclipse range of values.

Later in eclipse, the line profile presents absorption deeper than the maximum observed out–of–eclipse. In addition, our observations 2010–11–15 through 2010–11–24 show both polarized flux and %p are also broadly present across the line and include the line core (Fig. 5.8). Polarized flux returns to zero after 4th contact.

The line profile changes and EW fluctuations during eclipse could be within the normal photospheric variation of the line, but the polarization behavior is similar to lines with obvious disk absorption features. The polarization suggests that there is some contribution from scattering at disk material during eclipse, even if additional disk absorption is not evident in the equivalent widths. In this case, the scattering and absorption are not occurring at the same location on the disk.

Mg II (448.133 nm). The Mg II 448.133 nm line presents similar eclipse behavior to Si II 634.710 nm. The medium strength absorption line also arises from a high energy (E_\| > 3 eV) transition (E_\| = 8.86 eV, E_\perp = 11.63 eV). The equivalent width of the line does not change dramatically in our spectra and there are no large disk absorption or transient features during eclipse. The line exhibits an increase in polarized flux near 3rd contact (Fig. 5.11).

Figure 5.10 shows the unbinned intensity, binned %q and binned %u (bin size 0.008 nm) for Si II 634.710 nm and Mg II 448.133 nm for the same observation
taken about 2 months after mid–eclipse. The data are rotated into the stellar/disk reference frame and adjusted for F0 star motion. Disk rotation is evident in the reversal of Stokes $U (\%u)$ in both spectra. Stokes $Q (\%q)$ does not contribute to the Si $\text{II}$ 634.710 nm polarization. There is a sign reversal in $\%q$ across the Mg $\text{II}$ 448.133 nm line, with positive $\%q$ in the line core, negative $\%q$ in the red wing and no contribution from $\%q$ in the blue wing. The net effect is a loop that moves through 3 of 4 quadrants in a $q, u$–plot (Fig. 5.13).

The position angles are different for each segment of the Mg $\text{II}$ 448.133 nm absorption line in our 2010–10–16 observation, transitioning from 45° in the blue wing, through 0° (equivalent to 180°) at the line core and ending at near 90° in the red wing. The line is not significantly polarized in our out–of–eclipse spectra suggesting that this signal is an imprint of disk rotation on an otherwise unpolarized high energy transition. This polarization behavior is unexpected because of the sign reversal in $\%q$ which we expect to remain symmetric through the line (Milić and Faurobert, 2014). Ferluga and Mangiacapra (1991) used the Mg $\text{II}$ 448.133 nm line as an F0 star standard for shell line extraction; the authors made no comment regarding any possible blend. We find no suitable polarizable transitions as a possible blend candidate in NIST spectra³ (Kramida et al., 2014) and conclude that the signal we observe is due to the Mg $\text{II}$ 448.133 nm transition.

5.5.5 Spectral lines with disk absorption during eclipse

$\text{Ca I} (422.673 \text{ nm})$. The medium strength Ca $\text{I}$ 422.673 nm absorption line arises from a ground state transition. The line has obvious contributions to equivalent width from disk absorption, but the EW is variable throughout eclipse. Polarized

³Online http://physics.nist.gov
flux EW presents similar behavior, but greater amplitude, than many of the lines presented here. Compare this line to Fe II 531.661 nm (Fig. 5.17), for example.

\textbf{Fe II (519.757 nm, 527.600 nm, 531.661 nm)}. The Fe II lines 527.600 nm and 531.661 nm are two lines of the same multiplet with similar transition energies (527.600 nm, E_{ll} = 3.20, E_{ul} = 5.55; 531.661 nm, E_{ll} = 3.15, E_{ul} = 5.48). The lines present similar spectral features in both eclipse and out–of–eclipse spectra. Fe II 527.600 nm is slightly stronger (larger EW) than Fe II 531.661 nm in out–of–eclipse spectra. A third line, Fe II 519.757 nm, is a weaker line of the same multiplet (E_{ll} = 3.23, E_{ul} = 5.62) (Chapter 4).

We observe similar scattering behavior in these multiplet lines. The equivalent widths of the two Fe II lines 527.600 nm and 531.661 nm are variable between 1\textsuperscript{st} contact and 2\textsuperscript{nd} contact (Figs. 5.16 & 5.17). The equivalent width increases after 1\textsuperscript{st} contact (RJD 5079, 5080, 5083, and 5086) in both lines and then decreases. The EW increases again by about 5\% in early January 2010 (2010–01–02, RJD 5198) in the Fe II 527.600 nm line, from the minimum EW observed in late November 2009 (2009–11–29, RJD 5165). This increase occurs more than a month before 2\textsuperscript{nd} contact. A similar increase is not observed in the Fe II 531.661 nm line.

5.5.6 High eccentricity lines

Strassmeier et al. (2014) identified 15 lines whose orbital solution indicated high eccentricity. These lines are generally characterized by a high excitation potential and they originate from disk regions with higher eccentricity and higher rotational velocity. Seven of these lines are optically thick lines: four Balmer series lines, H\textalpha through H\gamma (656.280 nm, 486.135 nm, 434.047 nm, 410.173 nm), and the three Ca II infrared (IR) triplet transitions (849.802 nm, 854.209 nm, 866.214 nm). We present
detailed spectropolarimetric analysis of two Balmer series lines and one Ca i IR triplet line. We observe more scattered light (higher polarized flux EW) in these lines between 1\textsuperscript{st} and 2\textsuperscript{nd} contact than the less optically–thick lines.

\texttt{H\,i (656.280 \,nm; H\alpha)}. The Balmer series lines arise from a high energy lower level ($E_{ll} = 10.2$ eV). They are strong lines, optically thick at the line core and become very deep and sometimes saturated in eclipse (Geise et al., 2012). The H\alpha equivalent width increases dramatically in our spectra at mid–eclipse and then decreases steadily until 3\textsuperscript{rd} contact (Fig. 5.21). Polarized flux increases after 1\textsuperscript{st} contact, decreases near 2\textsuperscript{nd} contact and then increases again at mid–eclipse. The polarized flux remains high until 3\textsuperscript{rd} contact (Fig. 5.21).

Figure 5.21 shows the complicated polarization in the H\alpha line observed on 2010–11–15, four months after mid–eclipse and about 3 months before 3\textsuperscript{rd} contact. The data are not adjusted for F0 star motion (RV $-1.7$ km s$^{-1}$). The line polarization primarily probes blue–shifted rotating gas in this epoch. The line consists of a deep, wide blue–shifted absorption as well as less deep red–shifted absorption. The emission wings are not present and are likely filled–in by additional velocity–shifted absorption on both sides of the line core. The Stokes parameters probe four velocity regimes: (1) red–shifted absorption (+15 km s$^{-1}$) at ($-\%q,-\%u$), (2) low negative velocity material ($-15$ km s$^{-1}$) at ($-\%q,+\%u$), (3) medium negative velocity ($-50$ km s$^{-1}$) at ($+\%q, 0.0$) and (4) high negative velocity ($-130$ km s$^{-1}$) at ($+\%q,-\%u$). High blue–shifted (negative) velocity gas is closer to disk center and low blue–shifted (negative) velocity gas is outer disk material in this observation. Low velocity gas has the signature of disk rotation but also the imprint of the underlying F0 star polarization.
The four regimes consist of the following. (1) The red–shifted component consists of partially polarized F0 star photospheric light originating from low optical depth regions that may be multiply–scattered and polarized in the process, first by gas in the F0 star photosphere and then by the rotating gas in the disk. (2) The low velocity line core component consists of partially–polarized F0 star photospheric light from optically thick regions that may also be multiply–scattered, first in the photosphere and then by the rotating gas. The imprint of the disk rotation can be seen in the resulting PA. (3) The medium blue–shifted component consists of partially polarized F0 star photospheric light from low optical depth regions which is absorbed and scattered by rotating neutral hydrogen gas near the outer disk. (4) The highest velocity blue–shifted component arises from unpolarized F0 star light absorbed and scattered by rotating neutral hydrogen gas near the center of the disk. A more robust model would consider the scattering events in the disk frame of reference to include the relative velocities between the disk material and the F0 star photons for this observation.

Finally, we observe that Stokes $U$ ($\%u$) changes from negative at the H$\alpha$ line core in pre–eclipse observations to positive at the line core for post–eclipse observations (Fig. 5.23). Stokes $U$ ($\%u$) is negative before eclipse, is complex during mid–eclipse epochs and then becomes positive by 2011–08–17 (RJD 5791; phase 0.129) at 4th contact. The Stokes $U$ profile remains positive in our most recent observation (2012–12–09). The line returns to its pre–eclipse shape although with smaller emission wings (Fig. 5.22).

$H\alpha$ ($486.135 \text{ nm}$; $H\beta$). Similar to H$\alpha$, the H$\beta$ equivalent width increases dramatically at mid–eclipse and then decreases steadily until 3rd contact (Fig. 5.23). Polarized flux increases after 1st contact, decreases near 2nd contact and then increases
again at mid–eclipse. Unlike Hα, the polarized flux decreases after mid–eclipse until 3rd contact (Fig. 5.23). The line has a red–shifted absorption component by 1st contact and polarization in the blue wing at high negative velocities (−100 km s⁻¹, Fig 5.24). The line–of–sight disk material is largely rotating away from the viewer at early photometric eclipse epochs. The far blue wing polarization appears to probe disk material that extends above and below the disk, near disk center, that is rotating toward the viewer.

\textit{Ca} ii (866.214 nm). The Ca ii infrared (IR) triplet lines are characterized as low energy ($E_\| < 3 \text{ eV}$) but high eccentricity ($e > 0.3$) (Strassmeier et al., 2014). The Ca ii 866.214 nm line is unusual because the peak polarization occurs before 2nd contact rather than near 3rd contact as with other lines presented here. The equivalent width remains high after 4th contact (Fig. 5.25) perhaps because of gas trailing behind the dusty opaque disk (Griffin and Stencel, 2013). We observe a red–shifted line core in the intensity spectrum and polarization into the far blue wing in the epoch corresponding to the peak polarized flux EW (2009–12–02, RJD 55168).

5.6 Discussion

Scattered light contributes to polarization signatures in some lines even when the equivalent width of the line measured during eclipse is not noticeably larger or smaller than the EW measured out–of–eclipse. Scattered light measured by an increase in polarized flux EW is greatest after mid–eclipse and during the months leading up to 3rd contact. Polarized flux decreases in all lines by 4th contact.

5.6.1 Scattered light at mid–eclipse

Ferluga and Mangiacapra (1991) found in their mid–eclipse observations that the lines of the primary were much weaker than expected from known F0 star variability.
The authors explored the possibility that the superposition of another continuum could act to veil (fill–in) the absorption features. Ferluga and Mangiacapra achieved some improvement by scaling an observed UV excess and adding visible flux to their spectra but concluded the results did not match well with observations. They also considered the addition of light emitted at resonance wavelengths from UV excitation of gas in the disk. They found that the dilution affected disk lines as well as the lines of the primary which was inconsistent with their observations. They concluded that the weakening of absorption features at mid–eclipse affected only the lines of the primary (F0 star) and not of the secondary. The authors left the issue unresolved.

Saito et al. (1987) found that the scattered light in the system seems to have a spectrum almost similar to the primary (F0 star) spectrum with some extinction due to the secondary matter. Saito et al. attributed the scattering to large dust grains (10–100 µm) throughout eclipse and surmised that as much as 30% of the light observed in the system was scattered light (Saito et al., 1987, Appendix A). Large dust grains scatter incident light nearly completely forward.

We observe that many lines are polarized in ESPaDOnS spectra taken around mid–eclipse. The lines carry the imprint of rotation or flow evidenced by an antisymmetric Stokes $U (\%u)$ profile. For high energy transitions, there is little or no additional disk absorption at resonant frequencies; the equivalent width of the line is largely unchanged from its out–of–eclipse values. In addition, significant polarization does not appear in many of these lines until mid–eclipse.

The relative number of scatterers (gas and dust) along the line–of–sight is uneven during eclipse because of the thermal gradient of the disk and its asymmetries.
(such as trailing material). The temperature of the dust, and coupled gas, peaks after mid–eclipse because of the thermal capacity of the bulk material in the disk (Pearson and Stencel, 2015). After mid–eclipse, the number of blue–shifted scatterers is greater than the number of red–shifted scatterers in the line–of–sight because the height of gas and dust above the disk is increased due to thermal expansion in the part of the disk rotating toward the viewer.

The observed effect of the interaction between incoming F0 star photons and disk material is that the incoming spectrum is velocity–shifted toward the blue at mid–eclipse and for periods shortly thereafter. For high energy transitions, the moving disk material imparts a frequency redistribution of the line profile without imparting additional absorption features to the spectrum. Given the interaction is largely gray for high energy transitions at mid–eclipse, the scattering agent may be large dust grains, rather than gas species because little or no additional absorption is observed in these lines (further discussion below).

The scatterers are moving toward the viewer at mid–eclipse epochs and may be confined to the disk region rotating toward the viewer, a wind or outflow associated with a nebulosity at disk center, or both. The polarization arises because the radiation is anisotropic (e.g. only one side of the disk is illuminated by the F0 star) and because the geometry of the scattering is asymmetric (e.g. confined to a disk). The result of interaction is that scattering events velocity–shift the incoming spectrum. The velocity–shifted polarization profile moves toward the line rest wavelength after mid–eclipse (Figs. 5.8 & 5.12). This suggests that the average velocity field of the scatterers decreases as the disk passes in front of the F0 star after mid–eclipse. Decreasing velocity with radius is consistent with disk material in Keplerian rotation.
5.6.2 Comparison to continuum polarization

Broadband (continuum) polarization measurements were taken in $B, V, R$ filters beginning after 2$^{\text{rd}}$ contact and continuing until about 6 months after the most recent (2009–2011) eclipse (Cole, 2012). Broadband ($U, B, V$) polarization measurements were also taken during and after the previous (1982–1984) eclipse (Kemp et al., 1986; Henson, 1989). Cole and Stencel (2011) observed a peak in broadband polarization during the recent eclipse at RJD 55600 ($\phi = 0.110$) near 3$^{\text{rd}}$ contact (Cole and Stencel, 2011, Fig. 1). We calculated the orbital phase for each broadband observation obtained from the literature using the ephemeris by Stefanik et al. (2010). We scaled the observations by taking the difference from the minimum %$p$ observed by each instrument ($\Delta$%$p$). We compared the continuum polarization between the two eclipses by plotting $\Delta$%$p$ by orbital phase (Fig. 5.27). We calculated the change (from the minimum) to the equivalent width of the polarized flux ($W_{pf}$) for each line ($\Delta W_{pf}$) and scaled each by an arbitrary amount to match the peak heights between the broadband and line observations. We then plotted the scaled $\Delta W_{pf}$ by orbital phase on the same plot as the broadband observations (Fig. 5.27). We observe that the broadband peak polarization was present in both eclipses and occurs at a later orbital phase than the peak observed in the polarized flux EW.

The primary polarization mechanism in the lines is coherent resonant (Rayleigh) scattering at neutral and singly-ionized atomic species (Stenflo et al., 2000; Stenflo, 2005). Rayleigh scattering at these atomic transitions is largest at a scattering angle of 90° from the direction of the radiation (Stenflo, 1996). The largest scattering angle possible for $\varepsilon$ Aurigae, given a distance of 740 pc, is about 15°. The continuum polarization likely arises from F0 star light interacting with forward-scattering dust grains (e.g. Saito et al., 1987). In the $\varepsilon$ Aurigae case, broadband and line polarization measurements taken at the same orbital phase probe slightly different parts
of the disk. The broadband polarization primarily probes the dust along the direct line–of–sight (the normal). The line polarization probes the gas at angles greater than the direct line–of–sight.

The “Rayleigh scattering halo” for gas is wider than the F0 star’s disk face and taller than the opaque disk height because it includes all angles from the F0 star that intersect the disk atmosphere (e.g. Budaj, 2012, Fig. 2). The peak in broadband polarization near 3rd contact lags behind the line polarization flux peak by ~90 days (Fig. 5.27). The lag occurs because the line polarization probes the disk at a scattering angle larger than the angle normal to the disk for any eclipse phase. The line polarization probes the thermally–enhanced scattering region prior to the continuum polarization because of the geometry of the eclipse.

We observe a polarization lag in lines with additional disk absorption features and in lines without additional disk absorption features. This points to Rayleigh scattering as the dominant mechanism in both types of line, rather than scattering by large dust grains suggested by Saito et al. (1987) or by electrons (Wood et al., 1993). The observed antisymmetric Stokes $U$ profile across both types of line, similar to the effect produced by rotating optically thick gas disk models (Milić and Faurobert, 2014), also points to Rayleigh scattering as the polarization mechanism.

5.6.3 Disk rotation

Milić and Faurobert (2014) modeled homogeneous, isothermal, centrally– and internally–illuminated, optically thick disks under moderate Keplerian rotation and found bi–lobed polarization amplitudes >4% for optical depth $\tau_r = 10^4$ at an inclination $i = 75^\circ$ (model B$_i$, Fig. 11, top). The rotational velocity considered was $v_{\text{rot}} \sim 10 v_D$, where $v_D$ is the Doppler velocity. Estimates of the rotation of the $\varepsilon$ Aurigae
disk vary from $\sim 30$ km s$^{-1}$ to $\sim 45$ km s$^{-1}$ (e.g. Leadbeater et al., 2012). Stencel et al. found a CO gas temperature of $1250 \pm 50$ K at mid–eclipse and intrinsic line broadening of 12 km s$^{-1}$, consistent with a previous study of CO molecular emission during eclipse (Hinkle and Simon, 1987). Stencel et al. (2015) found that the local turbulence could be dynamically significant if represented by the CO line widths. If $v_D = 12$ km s$^{-1}$, then $v_{\text{rot}} = 3v_D$, about a third less than the Milić and Faurobert models.

The $\varepsilon$ Aurigae geometry is significantly different from the Milić and Faurobert models because the central illumination (B star radiation) is undetectable in visible spectra. The F0 star is the dominant source of radiation contributing to line absorption during eclipse. The star is at least 9 AU from the edge of the disk (distance 740 pc) and the scattering angles are confined to be $< 15^\circ$ because of the geometry of the system (Pearson, private comm.).

We observe bi–lobed %p with amplitudes less than 1% in strong lines near and just after mid–eclipse, significantly less than the polarization produced by the Milić and Faurobert rotating optically thick disk models. The difference in the observed $\varepsilon$ Aurigae polarization and the models is likely due to the difference between the geometry of the $\varepsilon$ Aurigae system and the model geometry.

### 5.7 Conclusions and next steps

We observe the following.

- Many lines are polarized in spectra taken after mid–eclipse and they carry the imprint of rotation or flow evidenced by antisymmetric Stokes $U$ (%u) and position angle rotation across the line and a bi–lobed %p profile. Milić and Faurobert (2014) identified these polarimetric signatures as evidence for
rotation in models of optically thick disks. Our observations are consistent with the Milić and Faurobert models.

- The gaseous disk is a poor scatterer of visible light. Percent linear polarization ($\%p$) is less than 1% in strong lines even in epochs with the greatest observed polarization. The low levels of observed polarization may be due to efficient absorption by the opaque part of the disk, poor scattering angles for Rayleigh scattering imposed by the geometry, or the large distance between the disk and the dominant source of illumination.

- Polarized flux reaches a maximum for almost all polarized atomic transitions after mid–eclipse and before 3$^{rd}$ contact. This observation implies that the disk scale height is larger after mid–eclipse.

- The maximum polarized flux precedes the broadband polarization peak by $\sim$90 days. The line scattering mechanism is Rayleigh scattering which probes the edges of a gas ‘halo’ region wider than the direct line–of–sight probed by continuum scattering at dust or electrons.

Our group is actively involved in modeling the $\varepsilon$ Aurigae disk. This work may help describe disk morphology and constrain models of temperature gradients already underway. We intend to collaborate on a 3D model of the system that includes polarization in future.
This work is in preparation for submission: Kathleen Geise, Robert Stencil* & Nadine Manset*, 2015. This research has made use of the NIST Spectral database (Kramida et al., 2014).

*Based on observations obtained at the Canada-France-Hawaii Telescope (CFHT) which is operated by the National Research Council of Canada, the Institut National des Sciences de l’Univers of the Centre National de la Recherche Scientifique of France, and the University of Hawaii.
Table 5.1: Log of Observations

<table>
<thead>
<tr>
<th>UT Date</th>
<th>RJD(^a)</th>
<th>Phase(^b)</th>
<th>RV(^b) (km s(^{-1}))</th>
<th>Comments(^c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006 Feb 08</td>
<td>53774.92</td>
<td>0.926</td>
<td>13.99</td>
<td>Paper 1</td>
</tr>
<tr>
<td>2008 Aug 25</td>
<td>54704.04</td>
<td>0.019</td>
<td>9.00</td>
<td>Paper 1</td>
</tr>
<tr>
<td>2008 Oct 18</td>
<td>54757.92</td>
<td>0.025</td>
<td>8.40</td>
<td>Paper 1</td>
</tr>
<tr>
<td>2008 Dec 07</td>
<td>54807.82</td>
<td>0.030</td>
<td>7.82</td>
<td>Epoch–binned (54811)</td>
</tr>
<tr>
<td>2008 Dec 08</td>
<td>54808.83</td>
<td>0.030</td>
<td>7.81</td>
<td>Epoch–binned (54811)</td>
</tr>
<tr>
<td>2008 Dec 09</td>
<td>54809.83</td>
<td>0.030</td>
<td>7.80</td>
<td>Epoch–binned (54811)</td>
</tr>
<tr>
<td>2008 Dec 10</td>
<td>54810.83</td>
<td>0.030</td>
<td>7.79</td>
<td>Epoch–binned (54811)</td>
</tr>
<tr>
<td>2008 Dec 16</td>
<td>54817.05</td>
<td>0.031</td>
<td>7.71</td>
<td>···</td>
</tr>
<tr>
<td>2009 Feb 13</td>
<td>54875.71</td>
<td>0.036</td>
<td>7.01</td>
<td>Epoch–binned (54877)</td>
</tr>
<tr>
<td>2009 Feb 14</td>
<td>54876.70</td>
<td>0.037</td>
<td>7.00</td>
<td>Epoch–binned (54877)</td>
</tr>
<tr>
<td>2009 Feb 17</td>
<td>54879.85</td>
<td>0.037</td>
<td>6.96</td>
<td>Epoch–binned (54877)</td>
</tr>
<tr>
<td>2009 May 04</td>
<td>54955.72</td>
<td>0.045</td>
<td>6.02</td>
<td>···</td>
</tr>
<tr>
<td>2009 Aug 16</td>
<td>55070</td>
<td>0.056</td>
<td>···</td>
<td>1(^{st}) contact</td>
</tr>
<tr>
<td>2009 Sep 04</td>
<td>55079.05</td>
<td>0.057</td>
<td>4.46</td>
<td>Epoch–binned (55086)</td>
</tr>
<tr>
<td>2009 Sep 05</td>
<td>55080.07</td>
<td>0.057</td>
<td>4.44</td>
<td>Epoch–binned (55086)</td>
</tr>
<tr>
<td>2009 Sep 08</td>
<td>55083.15</td>
<td>0.057</td>
<td>4.40</td>
<td>Epoch–binned (55086)</td>
</tr>
<tr>
<td>2009 Sep 11</td>
<td>55086.11</td>
<td>0.058</td>
<td>4.37</td>
<td>Epoch–binned (55086)</td>
</tr>
<tr>
<td>2009 Sep 25</td>
<td>55100.05</td>
<td>0.059</td>
<td>4.19</td>
<td>Epoch–binned (55104)</td>
</tr>
<tr>
<td>2009 Sep 26</td>
<td>55101.02</td>
<td>0.059</td>
<td>4.17</td>
<td>Epoch–binned (55104)</td>
</tr>
<tr>
<td>2009 Sep 29</td>
<td>55104.03</td>
<td>0.060</td>
<td>4.14</td>
<td>Epoch–binned (55104)</td>
</tr>
<tr>
<td>2009 Oct 02</td>
<td>55107.02</td>
<td>0.060</td>
<td>4.10</td>
<td>Epoch–binned (55115)</td>
</tr>
<tr>
<td>2009 Oct 07</td>
<td>55112.01</td>
<td>0.060</td>
<td>4.03</td>
<td>Epoch–binned (55115)</td>
</tr>
<tr>
<td>2009 Oct 10</td>
<td>55115.16</td>
<td>0.061</td>
<td>3.99</td>
<td>Epoch–binned (55115)</td>
</tr>
<tr>
<td>2009 Nov 29</td>
<td>55165.11</td>
<td>0.066</td>
<td>3.35</td>
<td>···</td>
</tr>
<tr>
<td>2009 Dec 02</td>
<td>55168.00</td>
<td>0.066</td>
<td>3.31</td>
<td>Epoch–binned (55174)</td>
</tr>
<tr>
<td>2009 Dec 04</td>
<td>55169.80</td>
<td>0.066</td>
<td>3.29</td>
<td>Epoch–binned (55174)</td>
</tr>
<tr>
<td>2009 Dec 07</td>
<td>55173.14</td>
<td>0.067</td>
<td>3.25</td>
<td>Epoch–binned (55174)</td>
</tr>
<tr>
<td>2009 Dec 08</td>
<td>55174.14</td>
<td>0.067</td>
<td>3.23</td>
<td>Epoch–binned (55174)</td>
</tr>
<tr>
<td>2010 Jan 02</td>
<td>55198.77</td>
<td>0.069</td>
<td>2.92</td>
<td>···</td>
</tr>
<tr>
<td>2010 Jan 26</td>
<td>55222.71</td>
<td>0.072</td>
<td>2.61</td>
<td>Epoch–binned (55225)</td>
</tr>
<tr>
<td>2010 Jan 28</td>
<td>55224.70</td>
<td>0.072</td>
<td>2.58</td>
<td>Epoch–binned (55225)</td>
</tr>
<tr>
<td>2010 Feb 22</td>
<td>55250</td>
<td>0.074</td>
<td>···</td>
<td>2(^{nd}) contact</td>
</tr>
<tr>
<td>2010 Mar 08</td>
<td>55263.72</td>
<td>0.076</td>
<td>2.08</td>
<td>55264</td>
</tr>
<tr>
<td>2010 Jul 22</td>
<td>55400</td>
<td>0.088</td>
<td>···</td>
<td>mid–eclipse</td>
</tr>
<tr>
<td>2010 Jul 23</td>
<td>55401.12</td>
<td>0.090</td>
<td>0.34</td>
<td>···</td>
</tr>
<tr>
<td>2010 Aug 01</td>
<td>55410.13</td>
<td>0.090</td>
<td>0.23</td>
<td>Epoch–binned (55414)</td>
</tr>
<tr>
<td>2010 Aug 05</td>
<td>55414.11</td>
<td>0.091</td>
<td>0.18</td>
<td>Epoch–binned (55414)</td>
</tr>
</tbody>
</table>

Continued on Next Page...
<table>
<thead>
<tr>
<th>UT Date</th>
<th>RJD&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Phase&lt;sup&gt;b&lt;/sup&gt;</th>
<th>RV&lt;sup&gt;b&lt;/sup&gt; (km s&lt;sup&gt;−1&lt;/sup&gt;)</th>
<th>Comments&lt;sup&gt;c&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010 Oct 16</td>
<td>55485.91</td>
<td>0.098</td>
<td>−0.71</td>
<td>Epoch–binned (55489)</td>
</tr>
<tr>
<td>2010 Oct 18</td>
<td>55487.90</td>
<td>0.098</td>
<td>−0.73</td>
<td>Epoch–binned (55489)</td>
</tr>
<tr>
<td>2010 Oct 19</td>
<td>55488.99</td>
<td>0.098</td>
<td>−0.74</td>
<td>Epoch–binned (55489)</td>
</tr>
<tr>
<td>2010 Oct 21</td>
<td>55490.93</td>
<td>0.099</td>
<td>−0.77</td>
<td>Epoch–binned (55489)</td>
</tr>
<tr>
<td>2010 Nov 15</td>
<td>55516.02</td>
<td>0.101</td>
<td>−1.07</td>
<td>Epoch–binned (55518)</td>
</tr>
<tr>
<td>2010 Nov 16</td>
<td>55517.14</td>
<td>0.101</td>
<td>−1.08</td>
<td>Epoch–binned (55518)</td>
</tr>
<tr>
<td>2010 Nov 17</td>
<td>55517.96</td>
<td>0.101</td>
<td>−1.09</td>
<td>Epoch–binned (55518)</td>
</tr>
<tr>
<td>2010 Nov 22</td>
<td>55522.89</td>
<td>0.102</td>
<td>−1.15</td>
<td>Epoch–binned (55525)</td>
</tr>
<tr>
<td>2010 Nov 24</td>
<td>55524.99</td>
<td>0.102</td>
<td>−1.18</td>
<td>Epoch–binned (55525)</td>
</tr>
<tr>
<td>2010 Dec 17</td>
<td>55549.74</td>
<td>0.105</td>
<td>−1.47</td>
<td>55550</td>
</tr>
<tr>
<td>2011 Feb 27</td>
<td>55620</td>
<td>0.114</td>
<td>⋮</td>
<td>3&lt;sup&gt;rd&lt;/sup&gt; contact</td>
</tr>
<tr>
<td>2011 Aug 17</td>
<td>55791.13</td>
<td>0.129</td>
<td>−4.19</td>
<td>55791</td>
</tr>
<tr>
<td>2011 Aug 26</td>
<td>55800</td>
<td>0.130</td>
<td>⋮</td>
<td>4&lt;sup&gt;th&lt;/sup&gt; contact</td>
</tr>
<tr>
<td>2011 Nov 01</td>
<td>55867.13</td>
<td>0.137</td>
<td>−4.97</td>
<td>⋮</td>
</tr>
<tr>
<td>2011 Nov 15</td>
<td>55880.99</td>
<td>0.138</td>
<td>−5.11</td>
<td>Epoch–binned (55882)</td>
</tr>
<tr>
<td>2011 Nov 16</td>
<td>55882.16</td>
<td>0.138</td>
<td>−5.12</td>
<td>Epoch–binned (55882)</td>
</tr>
<tr>
<td>2012 Jan 06</td>
<td>55933.00</td>
<td>0.143</td>
<td>−5.62</td>
<td>Epoch–binned (55944)</td>
</tr>
<tr>
<td>2012 Jan 17</td>
<td>55943.78</td>
<td>0.144</td>
<td>−5.72</td>
<td>Epoch–binned (55944)</td>
</tr>
<tr>
<td>2012 Dec 09</td>
<td>56271.05</td>
<td>0.178</td>
<td>−8.51</td>
<td>56271</td>
</tr>
</tbody>
</table>

**Note:** ESPaDOnS observations of ε Aurigae. Epoch–binned data are indicated. Single epochs 2008–12–16 (RJD 54817), 2009–11–29 (RJD 55165), 2010–01–02 (RJD 55199), 2010–07–23 (RJD 55401), 2011–11–01 (RJD 55867) were excluded from polarized flux plots because of noisy data.

<sup>a</sup>RJD = Heliocentric Julian Date − 2,400,000

<sup>b</sup>F0 star, calculated using the ephemeris from Stefanik et al. (2010) 2434723 + 9896.0E

<sup>c</sup>Eclipse timings with uncertainties of one to two weeks by Stencel (2012). Compare the mid–eclipse epoch tabulated here with the predicted mid–eclipse time given as 2455413.8 ± 4.8, corresponding to 2010 August 05, by Stefanik et al. (2010). Out–of–eclipse observations (Paper 1) are discussed in Chapter 4.
Table 5.2: Equivalent width: Pre–eclipse to 2nd contact

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Species</th>
<th>Range</th>
<th>54811</th>
<th>54877</th>
<th>54956</th>
<th>55086</th>
<th>55104</th>
<th>55115</th>
<th>55174</th>
<th>55225</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Beg</td>
<td>End</td>
<td>EW</td>
<td>EW</td>
<td>EW</td>
<td>EW</td>
<td>EW</td>
<td>EW</td>
<td>EW</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(nm)</td>
<td>(nm)</td>
<td>(mA)</td>
<td>(mA)</td>
<td>(mA)</td>
<td>(mA)</td>
<td>(mA)</td>
<td>(mA)</td>
<td>(mA)</td>
</tr>
<tr>
<td>407.771</td>
<td>Sr II</td>
<td>650</td>
<td>31</td>
<td>620</td>
<td>715</td>
<td>763</td>
<td>796</td>
<td>660</td>
<td>677</td>
<td></td>
</tr>
<tr>
<td>410.173</td>
<td>H I</td>
<td>409.57</td>
<td>410.77</td>
<td>1770</td>
<td>1703</td>
<td>1750</td>
<td>1781</td>
<td>1754</td>
<td>1774</td>
<td>1778</td>
</tr>
<tr>
<td>417.212</td>
<td>Fe I</td>
<td>417.08</td>
<td>417.27</td>
<td>531</td>
<td>582</td>
<td>541</td>
<td>596</td>
<td>579</td>
<td>589</td>
<td>548</td>
</tr>
<tr>
<td>417.353</td>
<td>Ti II</td>
<td>417.26</td>
<td>417.48</td>
<td>787</td>
<td>803</td>
<td>783</td>
<td>834</td>
<td>852</td>
<td>864</td>
<td>804</td>
</tr>
<tr>
<td>421.552</td>
<td>Sr II</td>
<td>421.43</td>
<td>421.67</td>
<td>462</td>
<td>568</td>
<td>451</td>
<td>531</td>
<td>587</td>
<td>616</td>
<td>526</td>
</tr>
<tr>
<td>422.673</td>
<td>Ca I</td>
<td>422.60</td>
<td>422.83</td>
<td>461</td>
<td>584</td>
<td>473</td>
<td>536</td>
<td>636</td>
<td>676</td>
<td>570</td>
</tr>
<tr>
<td>422.733</td>
<td>Ti II</td>
<td>422.60</td>
<td>422.83</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>423.316</td>
<td>Fe II</td>
<td>423.10</td>
<td>423.50</td>
<td>809</td>
<td>822</td>
<td>798</td>
<td>879</td>
<td>877</td>
<td>873</td>
<td>904</td>
</tr>
<tr>
<td>432.095</td>
<td>Ti II</td>
<td>431.95</td>
<td>432.17</td>
<td>534</td>
<td>553</td>
<td>534</td>
<td>592</td>
<td>607</td>
<td>615</td>
<td>589</td>
</tr>
<tr>
<td>437.482</td>
<td>Ti II</td>
<td>437.32</td>
<td>437.60</td>
<td>687</td>
<td>777</td>
<td>692</td>
<td>740</td>
<td>792</td>
<td>820</td>
<td>706</td>
</tr>
<tr>
<td>438.538</td>
<td>Fe II</td>
<td>438.47</td>
<td>438.62</td>
<td>606</td>
<td>573</td>
<td>584</td>
<td>598</td>
<td>598</td>
<td>639</td>
<td>636</td>
</tr>
<tr>
<td>439.406</td>
<td>Ti II</td>
<td>439.27</td>
<td>439.67</td>
<td>1236</td>
<td>1297</td>
<td>1221</td>
<td>1376</td>
<td>1402</td>
<td>1414</td>
<td>1383</td>
</tr>
<tr>
<td>441.682</td>
<td>Fe II</td>
<td>441.61</td>
<td>441.87</td>
<td>1175</td>
<td>1214</td>
<td>1169</td>
<td>1290</td>
<td>1308</td>
<td>1304</td>
<td>1265</td>
</tr>
<tr>
<td>444.430</td>
<td>Ti II</td>
<td>444.25</td>
<td>444.55</td>
<td>954</td>
<td>999</td>
<td>935</td>
<td>1045</td>
<td>1076</td>
<td>1102</td>
<td>1056</td>
</tr>
<tr>
<td>444.456</td>
<td>Ti II</td>
<td>444.25</td>
<td>444.55</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>446.849</td>
<td>Ti II</td>
<td>446.71</td>
<td>447.00</td>
<td>782</td>
<td>814</td>
<td>743</td>
<td>876</td>
<td>888</td>
<td>893</td>
<td>899</td>
</tr>
<tr>
<td>448.832</td>
<td>Ti II</td>
<td>448.75</td>
<td>449.00</td>
<td>668</td>
<td>715</td>
<td>679</td>
<td>718</td>
<td>733</td>
<td>745</td>
<td>715</td>
</tr>
<tr>
<td>449.140</td>
<td>Fe II</td>
<td>449.00</td>
<td>449.25</td>
<td>458</td>
<td>451</td>
<td>449</td>
<td>496</td>
<td>482</td>
<td>480</td>
<td>502</td>
</tr>
<tr>
<td>450.127</td>
<td>Ti II</td>
<td>449.95</td>
<td>450.27</td>
<td>674</td>
<td>669</td>
<td>636</td>
<td>770</td>
<td>760</td>
<td>756</td>
<td>785</td>
</tr>
<tr>
<td>450.428</td>
<td>Fe II</td>
<td>450.67</td>
<td>450.95</td>
<td>587</td>
<td>565</td>
<td>564</td>
<td>648</td>
<td>623</td>
<td>618</td>
<td>663</td>
</tr>
<tr>
<td>451.533</td>
<td>Fe II</td>
<td>451.40</td>
<td>451.65</td>
<td>544</td>
<td>521</td>
<td>522</td>
<td>594</td>
<td>577</td>
<td>570</td>
<td>590</td>
</tr>
<tr>
<td>452.022</td>
<td>Fe II</td>
<td>451.91</td>
<td>452.14</td>
<td>533</td>
<td>512</td>
<td>516</td>
<td>592</td>
<td>567</td>
<td>558</td>
<td>590</td>
</tr>
<tr>
<td>452.263</td>
<td>Fe II</td>
<td>452.12</td>
<td>452.39</td>
<td>633</td>
<td>597</td>
<td>605</td>
<td>700</td>
<td>676</td>
<td>661</td>
<td>705</td>
</tr>
<tr>
<td>453.396</td>
<td>Ti II</td>
<td>453.26</td>
<td>453.52</td>
<td>737</td>
<td>724</td>
<td>700</td>
<td>836</td>
<td>824</td>
<td>822</td>
<td>833</td>
</tr>
</tbody>
</table>

Continued on Next Page...
Table 5.2 – Continued

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Species</th>
<th>Range</th>
<th>54811</th>
<th>54877</th>
<th>54956</th>
<th>55086</th>
<th>55104</th>
<th>55115</th>
<th>55174</th>
<th>55225</th>
</tr>
</thead>
<tbody>
<tr>
<td>454.152</td>
<td>Fe II</td>
<td>454.04</td>
<td>454.26</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>455.864</td>
<td>Cr II</td>
<td>455.72</td>
<td>455.97</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>456.376</td>
<td>Ti II</td>
<td>456.25</td>
<td>456.50</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>457.197</td>
<td>Ti II</td>
<td>457.05</td>
<td>457.32</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>457.633</td>
<td>Fe II</td>
<td>457.50</td>
<td>457.76</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>458.820</td>
<td>Cr II</td>
<td>455.00</td>
<td>459.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>459.205</td>
<td>Cr II</td>
<td>458.67</td>
<td>458.90</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>461.876</td>
<td>Fe I</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>461.881</td>
<td>Cr II</td>
<td>461.75</td>
<td>461.96</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>462.051</td>
<td>Fe II</td>
<td>461.96</td>
<td>462.15</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>462.929</td>
<td>Ti II</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>462.933</td>
<td>Fe II</td>
<td>462.78</td>
<td>463.08</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>467.041</td>
<td>Sc II</td>
<td>466.99</td>
<td>467.19</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>473.144</td>
<td>Fe II</td>
<td>473.00</td>
<td>473.28</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>480.509</td>
<td>Ti II</td>
<td>480.35</td>
<td>480.65</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>484.825</td>
<td>Cr II</td>
<td>484.69</td>
<td>484.95</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>486.135</td>
<td>H I</td>
<td>485.90</td>
<td>486.30</td>
<td>1554</td>
<td>1538</td>
<td>1568</td>
<td>1721</td>
<td>1667</td>
<td>1688</td>
<td>1693</td>
</tr>
<tr>
<td>487.649</td>
<td>Cr II</td>
<td>487.52</td>
<td>487.75</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>491.120</td>
<td>Ti II</td>
<td>490.99</td>
<td>491.25</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>492.392</td>
<td>Fe II</td>
<td>492.20</td>
<td>492.65</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>493.408</td>
<td>Ba II</td>
<td>493.20</td>
<td>493.60</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>495.760</td>
<td>Fe I</td>
<td>495.50</td>
<td>496.02</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>501.844</td>
<td>Fe II</td>
<td>501.60</td>
<td>502.10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>503.078</td>
<td>Fe I</td>
<td>502.95</td>
<td>503.21</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>512.916</td>
<td>Ti II</td>
<td>512.80</td>
<td>513.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>516.732</td>
<td>Mg I</td>
<td>516.60</td>
<td>516.78</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>516.890</td>
<td>Fe I</td>
<td>516.77</td>
<td>517.05</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Continued on Next Page...
<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Species</th>
<th>Range</th>
<th>54811</th>
<th>54877</th>
<th>54956</th>
<th>55086</th>
<th>55104</th>
<th>55115</th>
<th>55174</th>
<th>55225</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Beg</td>
<td>End</td>
<td>EW (mA)</td>
<td>EW (mA)</td>
<td>EW (mA)</td>
<td>EW (mA)</td>
<td>EW (mA)</td>
<td>EW (mA)</td>
<td>EW (mA)</td>
</tr>
<tr>
<td>516.903</td>
<td>Fe II</td>
<td>516.77</td>
<td>517.05</td>
<td>925</td>
<td>920</td>
<td>945</td>
<td>1052</td>
<td>1022</td>
<td>1010</td>
<td>1009</td>
</tr>
<tr>
<td>516.930(^{b})</td>
<td>Fe I</td>
<td>516.77</td>
<td>517.05</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>517.268</td>
<td>Mg I</td>
<td>517.05</td>
<td>517.45</td>
<td>429</td>
<td>520</td>
<td>436</td>
<td>486</td>
<td>523</td>
<td>507</td>
<td>509</td>
</tr>
<tr>
<td>518.360</td>
<td>Mg I</td>
<td>518.20</td>
<td>518.46</td>
<td>398</td>
<td>458</td>
<td>410</td>
<td>478</td>
<td>489</td>
<td>507</td>
<td>509</td>
</tr>
<tr>
<td>518.869</td>
<td>Ti II</td>
<td>518.74</td>
<td>519.00</td>
<td>406</td>
<td>414</td>
<td>402</td>
<td>470</td>
<td>466</td>
<td>475</td>
<td>467</td>
</tr>
<tr>
<td>519.757</td>
<td>Fe II</td>
<td>519.60</td>
<td>519.90</td>
<td>503</td>
<td>479</td>
<td>493</td>
<td>559</td>
<td>529</td>
<td>526</td>
<td>557</td>
</tr>
<tr>
<td>522.654</td>
<td>Ti II</td>
<td>522.52</td>
<td>522.80</td>
<td>509</td>
<td>568</td>
<td>500</td>
<td>565</td>
<td>587</td>
<td>603</td>
<td>561</td>
</tr>
<tr>
<td>523.462</td>
<td>Fe II</td>
<td>523.33</td>
<td>523.59</td>
<td>543</td>
<td>486</td>
<td>518</td>
<td>584</td>
<td>552</td>
<td>536</td>
<td>583</td>
</tr>
<tr>
<td>523.736</td>
<td>Cr II</td>
<td>523.57</td>
<td>523.88</td>
<td>297</td>
<td>294</td>
<td>303</td>
<td>323</td>
<td>306</td>
<td>302</td>
<td>314</td>
</tr>
<tr>
<td>525.496</td>
<td>Fe I</td>
<td>525.40</td>
<td>525.60</td>
<td>206</td>
<td>229</td>
<td>211</td>
<td>219</td>
<td>229</td>
<td>237</td>
<td>212</td>
</tr>
<tr>
<td>527.600</td>
<td>Fe II</td>
<td>527.35</td>
<td>527.85</td>
<td>836</td>
<td>818</td>
<td>827</td>
<td>921</td>
<td>885</td>
<td>881</td>
<td>892</td>
</tr>
<tr>
<td>528.442</td>
<td>Fe I</td>
<td>528.25</td>
<td>528.55</td>
<td>368</td>
<td>405</td>
<td>375</td>
<td>400</td>
<td>413</td>
<td>427</td>
<td>388</td>
</tr>
<tr>
<td>531.678</td>
<td>Fe II</td>
<td>531.45</td>
<td>531.90</td>
<td>763</td>
<td>720</td>
<td>734</td>
<td>862</td>
<td>812</td>
<td>795</td>
<td>858</td>
</tr>
<tr>
<td>533.679</td>
<td>Ti II</td>
<td>533.55</td>
<td>533.85</td>
<td>415</td>
<td>477</td>
<td>429</td>
<td>447</td>
<td>468</td>
<td>489</td>
<td>442</td>
</tr>
<tr>
<td>536.275</td>
<td>Fe II</td>
<td>536.15</td>
<td>536.40</td>
<td>431</td>
<td>420</td>
<td>421</td>
<td>472</td>
<td>450</td>
<td>447</td>
<td>457</td>
</tr>
<tr>
<td>538.102</td>
<td>Ti II</td>
<td>537.96</td>
<td>538.24</td>
<td>173</td>
<td>231</td>
<td>176</td>
<td>194</td>
<td>218</td>
<td>230</td>
<td>183</td>
</tr>
<tr>
<td>541.877</td>
<td>Ti II</td>
<td>541.74</td>
<td>542.02</td>
<td>98</td>
<td>144</td>
<td>98</td>
<td>107</td>
<td>131</td>
<td>143</td>
<td>112</td>
</tr>
<tr>
<td>552.679</td>
<td>Sc II</td>
<td>552.55</td>
<td>552.80</td>
<td>315</td>
<td>380</td>
<td>319</td>
<td>353</td>
<td>381</td>
<td>395</td>
<td>353</td>
</tr>
<tr>
<td>553.484</td>
<td>Fe II</td>
<td>553.34</td>
<td>553.62</td>
<td>349</td>
<td>357</td>
<td>350</td>
<td>377</td>
<td>363</td>
<td>369</td>
<td>370</td>
</tr>
<tr>
<td>565.791</td>
<td>Sc II</td>
<td>565.65</td>
<td>565.93</td>
<td>297</td>
<td>380</td>
<td>296</td>
<td>316</td>
<td>362</td>
<td>387</td>
<td>306</td>
</tr>
<tr>
<td>623.838</td>
<td>Fe II</td>
<td>623.69</td>
<td>623.99</td>
<td>254</td>
<td>315</td>
<td>276</td>
<td>262</td>
<td>260</td>
<td>275</td>
<td>255</td>
</tr>
<tr>
<td>624.756</td>
<td>Fe II</td>
<td>624.61</td>
<td>624.91</td>
<td>347</td>
<td>352</td>
<td>306</td>
<td>387</td>
<td>375</td>
<td>369</td>
<td>374</td>
</tr>
<tr>
<td>641.693</td>
<td>Fe II</td>
<td>641.54</td>
<td>641.84</td>
<td>171</td>
<td>166</td>
<td>171</td>
<td>185</td>
<td>176</td>
<td>178</td>
<td>179</td>
</tr>
<tr>
<td>643.268</td>
<td>Fe II</td>
<td>643.12</td>
<td>643.42</td>
<td>141</td>
<td>161</td>
<td>142</td>
<td>153</td>
<td>163</td>
<td>172</td>
<td>153</td>
</tr>
<tr>
<td>654.638</td>
<td>Fe II</td>
<td>654.45</td>
<td>654.80</td>
<td>482</td>
<td>467</td>
<td>486</td>
<td>534</td>
<td>499</td>
<td>496</td>
<td>517</td>
</tr>
<tr>
<td>651.608</td>
<td>Fe II</td>
<td>651.46</td>
<td>651.76</td>
<td>227</td>
<td>240</td>
<td>232</td>
<td>249</td>
<td>279</td>
<td>267</td>
<td>268</td>
</tr>
<tr>
<td>656.280</td>
<td>H I</td>
<td>655.84</td>
<td>656.71</td>
<td>606</td>
<td>531</td>
<td>699</td>
<td>827</td>
<td>683</td>
<td>888</td>
<td>555</td>
</tr>
</tbody>
</table>

Continued on Next Page...
Table 5.2 – Continued

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Species</th>
<th>Range Beg (nm)</th>
<th>Range End (nm)</th>
<th>EW (mA)</th>
<th>EW (mA)</th>
<th>EW (mA)</th>
<th>EW (mA)</th>
<th>EW (mA)</th>
<th>EW (mA)</th>
<th>EW (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>769.896</td>
<td>K I</td>
<td>769.79</td>
<td>770.00</td>
<td>611</td>
<td>598</td>
<td>595</td>
<td>680</td>
<td>654</td>
<td>648</td>
<td>688</td>
</tr>
</tbody>
</table>

**Note:** This table contains the equivalent width (EW) of total flux directly-integrated across the line (see text). Uncertainties < 1 mA throughout.

\(^{b}\)Blend.
<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Species</th>
<th>55264</th>
<th>55414</th>
<th>55489</th>
<th>55518</th>
<th>55525</th>
<th>55550</th>
<th>55791</th>
<th>55882</th>
<th>55944</th>
<th>56271</th>
</tr>
</thead>
<tbody>
<tr>
<td>407.771</td>
<td>Sr II</td>
<td>689</td>
<td>645</td>
<td>679</td>
<td>696</td>
<td>688</td>
<td>697</td>
<td>800</td>
<td>737</td>
<td>801</td>
<td>625</td>
</tr>
<tr>
<td>410.173</td>
<td>H I</td>
<td>1910</td>
<td>2121</td>
<td>2107</td>
<td>2150</td>
<td>2143</td>
<td>2118</td>
<td>1903</td>
<td>1824</td>
<td>1868</td>
<td>1717</td>
</tr>
<tr>
<td>417.212</td>
<td>Fe I</td>
<td>570</td>
<td>538</td>
<td>581</td>
<td>616</td>
<td>644</td>
<td>617</td>
<td>607</td>
<td>578</td>
<td>634</td>
<td>510</td>
</tr>
<tr>
<td>417.353</td>
<td>Ti II</td>
<td>857</td>
<td>875</td>
<td>860</td>
<td>909</td>
<td>930</td>
<td>929</td>
<td>924</td>
<td>847</td>
<td>874</td>
<td>746</td>
</tr>
<tr>
<td>421.552</td>
<td>Sr II</td>
<td>538</td>
<td>477</td>
<td>522</td>
<td>545</td>
<td>553</td>
<td>528</td>
<td>614</td>
<td>567</td>
<td>614</td>
<td>511</td>
</tr>
<tr>
<td>422.673</td>
<td>Ca I</td>
<td>627</td>
<td>537</td>
<td>613</td>
<td>684</td>
<td>696</td>
<td>610</td>
<td>723</td>
<td>586</td>
<td>606</td>
<td>507</td>
</tr>
<tr>
<td>422.733b</td>
<td>Ti II</td>
<td>…</td>
<td>…</td>
<td>…</td>
<td>…</td>
<td>…</td>
<td>…</td>
<td>…</td>
<td>…</td>
<td>…</td>
<td>…</td>
</tr>
<tr>
<td>423.316</td>
<td>Fe II</td>
<td>930</td>
<td>1014</td>
<td>1045</td>
<td>1097</td>
<td>1127</td>
<td>1152</td>
<td>1013</td>
<td>923</td>
<td>923</td>
<td>862</td>
</tr>
<tr>
<td>432.095</td>
<td>Ti II</td>
<td>581</td>
<td>575</td>
<td>571</td>
<td>609</td>
<td>631</td>
<td>645</td>
<td>716</td>
<td>612</td>
<td>659</td>
<td>542</td>
</tr>
<tr>
<td>434.047</td>
<td>H I</td>
<td>2160</td>
<td>2491</td>
<td>2490</td>
<td>2499</td>
<td>2480</td>
<td>2419</td>
<td>2197</td>
<td>2068</td>
<td>2130</td>
<td>1974</td>
</tr>
<tr>
<td>437.482</td>
<td>Ti II</td>
<td>712</td>
<td>703</td>
<td>756</td>
<td>793</td>
<td>800</td>
<td>784</td>
<td>882</td>
<td>803</td>
<td>884</td>
<td>721</td>
</tr>
<tr>
<td>438.538</td>
<td>Fe II</td>
<td>685</td>
<td>696</td>
<td>597</td>
<td>643</td>
<td>671</td>
<td>681</td>
<td>694</td>
<td>591</td>
<td>619</td>
<td>562</td>
</tr>
<tr>
<td>439.406</td>
<td>Ti II</td>
<td>1417</td>
<td>1442</td>
<td>1445</td>
<td>1516</td>
<td>1534</td>
<td>1517</td>
<td>1547</td>
<td>1387</td>
<td>1454</td>
<td>1208</td>
</tr>
<tr>
<td>441.682</td>
<td>Fe II</td>
<td>1291</td>
<td>1335</td>
<td>1329</td>
<td>1407</td>
<td>1402</td>
<td>1364</td>
<td>1400</td>
<td>1236</td>
<td>1339</td>
<td>1143</td>
</tr>
<tr>
<td>444.380</td>
<td>Ti II</td>
<td>1099</td>
<td>1099</td>
<td>1123</td>
<td>1189</td>
<td>1205</td>
<td>1195</td>
<td>1224</td>
<td>1072</td>
<td>1125</td>
<td>911</td>
</tr>
<tr>
<td>444.456b</td>
<td>Ti II</td>
<td>…</td>
<td>…</td>
<td>…</td>
<td>…</td>
<td>…</td>
<td>…</td>
<td>…</td>
<td>…</td>
<td>…</td>
<td>…</td>
</tr>
<tr>
<td>446.849</td>
<td>Ti II</td>
<td>902</td>
<td>953</td>
<td>937</td>
<td>1008</td>
<td>1029</td>
<td>1053</td>
<td>1040</td>
<td>917</td>
<td>946</td>
<td>750</td>
</tr>
<tr>
<td>448.832</td>
<td>Ti II</td>
<td>756</td>
<td>742</td>
<td>732</td>
<td>783</td>
<td>786</td>
<td>756</td>
<td>772</td>
<td>708</td>
<td>768</td>
<td>661</td>
</tr>
<tr>
<td>449.140</td>
<td>Fe II</td>
<td>507</td>
<td>535</td>
<td>501</td>
<td>547</td>
<td>565</td>
<td>569</td>
<td>532</td>
<td>478</td>
<td>515</td>
<td>443</td>
</tr>
<tr>
<td>450.127</td>
<td>Ti II</td>
<td>769</td>
<td>808</td>
<td>797</td>
<td>832</td>
<td>857</td>
<td>923</td>
<td>892</td>
<td>766</td>
<td>785</td>
<td>658</td>
</tr>
<tr>
<td>450.828</td>
<td>Fe II</td>
<td>669</td>
<td>723</td>
<td>705</td>
<td>756</td>
<td>785</td>
<td>818</td>
<td>702</td>
<td>616</td>
<td>654</td>
<td>572</td>
</tr>
<tr>
<td>451.533</td>
<td>Fe II</td>
<td>614</td>
<td>649</td>
<td>635</td>
<td>678</td>
<td>701</td>
<td>743</td>
<td>620</td>
<td>551</td>
<td>590</td>
<td>504</td>
</tr>
<tr>
<td>452.022</td>
<td>Fe II</td>
<td>601</td>
<td>635</td>
<td>613</td>
<td>655</td>
<td>681</td>
<td>715</td>
<td>609</td>
<td>540</td>
<td>585</td>
<td>494</td>
</tr>
<tr>
<td>452.263</td>
<td>Fe II</td>
<td>727</td>
<td>808</td>
<td>801</td>
<td>849</td>
<td>880</td>
<td>949</td>
<td>747</td>
<td>658</td>
<td>680</td>
<td>599</td>
</tr>
<tr>
<td>453.396</td>
<td>Ti II</td>
<td>865</td>
<td>918</td>
<td>908</td>
<td>951</td>
<td>983</td>
<td>1060</td>
<td>962</td>
<td>836</td>
<td>835</td>
<td>704</td>
</tr>
</tbody>
</table>

Continued on Next Page...
<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Species</th>
<th>55264</th>
<th>55414</th>
<th>55489</th>
<th>55518</th>
<th>55525</th>
<th>55550</th>
<th>55791</th>
<th>55882</th>
<th>55944</th>
<th>56271</th>
</tr>
</thead>
<tbody>
<tr>
<td>454.152</td>
<td>Fe II</td>
<td>447</td>
<td>448</td>
<td>425</td>
<td>462</td>
<td>474</td>
<td>468</td>
<td>439</td>
<td>397</td>
<td>437</td>
<td>370</td>
</tr>
<tr>
<td>455.864</td>
<td>Cr II</td>
<td>577</td>
<td>639</td>
<td>612</td>
<td>670</td>
<td>692</td>
<td>726</td>
<td>597</td>
<td>535</td>
<td>577</td>
<td>508</td>
</tr>
<tr>
<td>456.376</td>
<td>Ti II</td>
<td>771</td>
<td>801</td>
<td>807</td>
<td>847</td>
<td>876</td>
<td>939</td>
<td>883</td>
<td>767</td>
<td>785</td>
<td>660</td>
</tr>
<tr>
<td>457.197</td>
<td>Ti II</td>
<td>771</td>
<td>828</td>
<td>827</td>
<td>860</td>
<td>892</td>
<td>975</td>
<td>884</td>
<td>764</td>
<td>776</td>
<td>658</td>
</tr>
<tr>
<td>457.633</td>
<td>Fe II</td>
<td>463</td>
<td>455</td>
<td>442</td>
<td>475</td>
<td>489</td>
<td>492</td>
<td>461</td>
<td>417</td>
<td>455</td>
<td>397</td>
</tr>
<tr>
<td>458.820</td>
<td>Cr II</td>
<td>514</td>
<td>534</td>
<td>529</td>
<td>577</td>
<td>596</td>
<td>618</td>
<td>526</td>
<td>490</td>
<td>521</td>
<td>493</td>
</tr>
<tr>
<td>459.205</td>
<td>Cr II</td>
<td>305</td>
<td>299</td>
<td>286</td>
<td>317</td>
<td>320</td>
<td>298</td>
<td>318</td>
<td>287</td>
<td>316</td>
<td>270</td>
</tr>
<tr>
<td>461.876</td>
<td>Fe I</td>
<td>443</td>
<td>465</td>
<td>443</td>
<td>491</td>
<td>500</td>
<td>502</td>
<td>442</td>
<td>412</td>
<td>458</td>
<td>406</td>
</tr>
<tr>
<td>461.881</td>
<td>Cr II</td>
<td>351</td>
<td>345</td>
<td>327</td>
<td>348</td>
<td>354</td>
<td>330</td>
<td>348</td>
<td>307</td>
<td>350</td>
<td>308</td>
</tr>
<tr>
<td>462.051</td>
<td>Fe II</td>
<td>688</td>
<td>744</td>
<td>724</td>
<td>780</td>
<td>804</td>
<td>846</td>
<td>706</td>
<td>625</td>
<td>681</td>
<td>599</td>
</tr>
<tr>
<td>462.933</td>
<td>Fe II</td>
<td>372</td>
<td>343</td>
<td>355</td>
<td>385</td>
<td>385</td>
<td>344</td>
<td>391</td>
<td>348</td>
<td>393</td>
<td>316</td>
</tr>
<tr>
<td>467.041</td>
<td>Sc II</td>
<td>406</td>
<td>405</td>
<td>384</td>
<td>423</td>
<td>431</td>
<td>418</td>
<td>401</td>
<td>373</td>
<td>419</td>
<td>353</td>
</tr>
<tr>
<td>473.144</td>
<td>Fe II</td>
<td>432</td>
<td>418</td>
<td>420</td>
<td>460</td>
<td>475</td>
<td>472</td>
<td>470</td>
<td>419</td>
<td>466</td>
<td>386</td>
</tr>
<tr>
<td>480.509</td>
<td>Ti II</td>
<td>419</td>
<td>453</td>
<td>438</td>
<td>481</td>
<td>482</td>
<td>456</td>
<td>445</td>
<td>411</td>
<td>466</td>
<td>387</td>
</tr>
<tr>
<td>484.825</td>
<td>Cr II</td>
<td>1895</td>
<td>2630</td>
<td>2587</td>
<td>2524</td>
<td>2466</td>
<td>2340</td>
<td>1839</td>
<td>1760</td>
<td>1814</td>
<td>1590</td>
</tr>
<tr>
<td>486.135</td>
<td>H I</td>
<td>345</td>
<td>355</td>
<td>337</td>
<td>367</td>
<td>372</td>
<td>356</td>
<td>351</td>
<td>327</td>
<td>359</td>
<td>321</td>
</tr>
<tr>
<td>487.649</td>
<td>Cr II</td>
<td>304</td>
<td>279</td>
<td>289</td>
<td>317</td>
<td>315</td>
<td>285</td>
<td>309</td>
<td>286</td>
<td>322</td>
<td>273</td>
</tr>
<tr>
<td>491.120</td>
<td>Ti II</td>
<td>1015</td>
<td>1219</td>
<td>1275</td>
<td>1330</td>
<td>1364</td>
<td>1409</td>
<td>1118</td>
<td>1031</td>
<td>1010</td>
<td>877</td>
</tr>
<tr>
<td>492.392</td>
<td>Fe II</td>
<td>217</td>
<td>146</td>
<td>174</td>
<td>216</td>
<td>207</td>
<td>171</td>
<td>242</td>
<td>217</td>
<td>254</td>
<td>169</td>
</tr>
<tr>
<td>493.408</td>
<td>Ba II</td>
<td>292</td>
<td>249</td>
<td>270</td>
<td>302</td>
<td>292</td>
<td>257</td>
<td>297</td>
<td>272</td>
<td>312</td>
<td>247</td>
</tr>
<tr>
<td>501.841</td>
<td>Fe II</td>
<td>301</td>
<td>265</td>
<td>279</td>
<td>312</td>
<td>314</td>
<td>283</td>
<td>340</td>
<td>297</td>
<td>345</td>
<td>258</td>
</tr>
<tr>
<td>503.078</td>
<td>Fe I</td>
<td>304</td>
<td>259</td>
<td>249</td>
<td>289</td>
<td>292</td>
<td>273</td>
<td>338</td>
<td>283</td>
<td>332</td>
<td>246</td>
</tr>
<tr>
<td>512.916</td>
<td>Ti II</td>
<td>308</td>
<td>323</td>
<td>463</td>
<td>498</td>
<td>480</td>
<td>426</td>
<td>353</td>
<td>318</td>
<td>358</td>
<td>282</td>
</tr>
<tr>
<td>516.732</td>
<td>Mg I</td>
<td>1128</td>
<td>1374</td>
<td>1364</td>
<td>1408</td>
<td>1448</td>
<td>1498</td>
<td>1263</td>
<td>1120</td>
<td>1114</td>
<td>945</td>
</tr>
</tbody>
</table>

Continued on Next Page...
<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Species</th>
<th>55264</th>
<th>55414</th>
<th>55489</th>
<th>55518</th>
<th>55525</th>
<th>55550</th>
<th>55791</th>
<th>55882</th>
<th>55944</th>
<th>56271</th>
</tr>
</thead>
<tbody>
<tr>
<td>516.930</td>
<td>Fe I</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>517.268</td>
<td>Mg I</td>
<td>549</td>
<td>509</td>
<td>553</td>
<td>649</td>
<td>664</td>
<td>643</td>
<td>571</td>
<td>484</td>
<td>544</td>
<td>426</td>
</tr>
<tr>
<td>518.360</td>
<td>Mg I</td>
<td>530</td>
<td>490</td>
<td>532</td>
<td>640</td>
<td>668</td>
<td>673</td>
<td>534</td>
<td>453</td>
<td>503</td>
<td>394</td>
</tr>
<tr>
<td>518.869</td>
<td>Ti II</td>
<td>443</td>
<td>444</td>
<td>438</td>
<td>488</td>
<td>512</td>
<td>534</td>
<td>553</td>
<td>452</td>
<td>515</td>
<td>379</td>
</tr>
<tr>
<td>519.757</td>
<td>Fe II</td>
<td>544</td>
<td>647</td>
<td>626</td>
<td>672</td>
<td>694</td>
<td>744</td>
<td>634</td>
<td>544</td>
<td>601</td>
<td>491</td>
</tr>
<tr>
<td>522.654</td>
<td>Ti II</td>
<td>554</td>
<td>556</td>
<td>602</td>
<td>651</td>
<td>654</td>
<td>644</td>
<td>665</td>
<td>579</td>
<td>637</td>
<td>499</td>
</tr>
<tr>
<td>523.462</td>
<td>Fe II</td>
<td>594</td>
<td>707</td>
<td>659</td>
<td>711</td>
<td>743</td>
<td>799</td>
<td>661</td>
<td>563</td>
<td>610</td>
<td>490</td>
</tr>
<tr>
<td>523.736</td>
<td>Cr II</td>
<td>310</td>
<td>342</td>
<td>310</td>
<td>337</td>
<td>351</td>
<td>339</td>
<td>326</td>
<td>307</td>
<td>339</td>
<td>285</td>
</tr>
<tr>
<td>525.496</td>
<td>Fe I</td>
<td>231</td>
<td>224</td>
<td>224</td>
<td>248</td>
<td>247</td>
<td>227</td>
<td>253</td>
<td>223</td>
<td>252</td>
<td>208</td>
</tr>
<tr>
<td>527.600</td>
<td>Fe II</td>
<td>920</td>
<td>1026</td>
<td>1008</td>
<td>1037</td>
<td>1059</td>
<td>1124</td>
<td>978</td>
<td>866</td>
<td>938</td>
<td>803</td>
</tr>
<tr>
<td>528.442</td>
<td>Fe I</td>
<td>411</td>
<td>406</td>
<td>404</td>
<td>437</td>
<td>440</td>
<td>433</td>
<td>439</td>
<td>395</td>
<td>440</td>
<td>362</td>
</tr>
<tr>
<td>531.678</td>
<td>Fe II</td>
<td>863</td>
<td>1028</td>
<td>1025</td>
<td>1080</td>
<td>1111</td>
<td>1192</td>
<td>948</td>
<td>829</td>
<td>885</td>
<td>738</td>
</tr>
<tr>
<td>533.679</td>
<td>Ti II</td>
<td>469</td>
<td>442</td>
<td>436</td>
<td>489</td>
<td>491</td>
<td>449</td>
<td>524</td>
<td>457</td>
<td>530</td>
<td>400</td>
</tr>
<tr>
<td>536.275</td>
<td>Fe II</td>
<td>469</td>
<td>524</td>
<td>487</td>
<td>526</td>
<td>542</td>
<td>568</td>
<td>496</td>
<td>437</td>
<td>501</td>
<td>410</td>
</tr>
<tr>
<td>538.102</td>
<td>Ti II</td>
<td>210</td>
<td>172</td>
<td>186</td>
<td>216</td>
<td>211</td>
<td>187</td>
<td>238</td>
<td>196</td>
<td>241</td>
<td>169</td>
</tr>
<tr>
<td>541.877</td>
<td>Ti II</td>
<td>128</td>
<td>100</td>
<td>115</td>
<td>140</td>
<td>137</td>
<td>107</td>
<td>159</td>
<td>127</td>
<td>159</td>
<td>106</td>
</tr>
<tr>
<td>552.679</td>
<td>Sc II</td>
<td>357</td>
<td>321</td>
<td>348</td>
<td>374</td>
<td>380</td>
<td>382</td>
<td>402</td>
<td>350</td>
<td>414</td>
<td>306</td>
</tr>
<tr>
<td>553.484</td>
<td>Fe II</td>
<td>381</td>
<td>404</td>
<td>379</td>
<td>413</td>
<td>424</td>
<td>419</td>
<td>410</td>
<td>364</td>
<td>412</td>
<td>343</td>
</tr>
<tr>
<td>565.791</td>
<td>Sc II</td>
<td>344</td>
<td>300</td>
<td>332</td>
<td>382</td>
<td>374</td>
<td>327</td>
<td>417</td>
<td>349</td>
<td>406</td>
<td>306</td>
</tr>
<tr>
<td>623.838</td>
<td>Fe II</td>
<td>326</td>
<td>337</td>
<td>338</td>
<td>354</td>
<td>349</td>
<td>346</td>
<td>294</td>
<td>299</td>
<td>381</td>
<td>343</td>
</tr>
<tr>
<td>624.756</td>
<td>Fe II</td>
<td>397</td>
<td>449</td>
<td>376</td>
<td>446</td>
<td>462</td>
<td>445</td>
<td>397</td>
<td>340</td>
<td>432</td>
<td>346</td>
</tr>
<tr>
<td>641.693</td>
<td>Fe II</td>
<td>187</td>
<td>201</td>
<td>177</td>
<td>205</td>
<td>209</td>
<td>196</td>
<td>201</td>
<td>173</td>
<td>210</td>
<td>160</td>
</tr>
<tr>
<td>643.268</td>
<td>Fe II</td>
<td>156</td>
<td>145</td>
<td>145</td>
<td>173</td>
<td>174</td>
<td>153</td>
<td>198</td>
<td>164</td>
<td>202</td>
<td>144</td>
</tr>
<tr>
<td>645.638</td>
<td>Fe II</td>
<td>530</td>
<td>664</td>
<td>627</td>
<td>676</td>
<td>687</td>
<td>698</td>
<td>573</td>
<td>511</td>
<td>570</td>
<td>453</td>
</tr>
<tr>
<td>651.608</td>
<td>Fe II</td>
<td>240</td>
<td>245</td>
<td>255</td>
<td>288</td>
<td>309</td>
<td>315</td>
<td>293</td>
<td>264</td>
<td>301</td>
<td>241</td>
</tr>
<tr>
<td>656.220</td>
<td>Fe II</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>656.280</td>
<td>H I</td>
<td>1308</td>
<td>4412</td>
<td>3937</td>
<td>3566</td>
<td>3278</td>
<td>2759</td>
<td>1261</td>
<td>1177</td>
<td>1445</td>
<td>842</td>
</tr>
</tbody>
</table>

Continued on Next Page...
Table 5.3 – Continued

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Species</th>
<th>EW (mA)</th>
<th>EW (mA)</th>
<th>EW (mA)</th>
<th>EW (mA)</th>
<th>EW (mA)</th>
<th>EW (mA)</th>
<th>EW (mA)</th>
<th>EW (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>769.896</td>
<td>K I</td>
<td>688</td>
<td>744</td>
<td>724</td>
<td>780</td>
<td>804</td>
<td>846</td>
<td>706</td>
<td>625</td>
</tr>
</tbody>
</table>

Note: This table contains the equivalent width (EW) of total flux directly-integrated across the line (see text). Uncertainties < 1 mA throughout.

b Blend.
<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Species</th>
<th>54811$^a$</th>
<th>54877$^a$</th>
<th>54956</th>
<th>55086$^a$</th>
<th>55104$^a$</th>
<th>55115$^a$</th>
<th>55174$^a$</th>
<th>55225$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>EW (mA)</td>
<td>EW (mA)</td>
<td>EW (mA)</td>
<td>EW (mA)</td>
<td>EW (mA)</td>
<td>EW (mA)</td>
<td>EW (mA)</td>
<td>EW (mA)</td>
</tr>
<tr>
<td>407.771</td>
<td>Sr II</td>
<td>1.0 ± 0.3</td>
<td>...</td>
<td>...</td>
<td>0.9 ± 0.3</td>
<td>...</td>
<td>1.6 ± 0.4</td>
<td>1.2 ± 0.3</td>
<td></td>
</tr>
<tr>
<td>410.173</td>
<td>H I</td>
<td>...</td>
<td>...</td>
<td>0.7 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>1.5 ± 0.3</td>
<td>...</td>
<td></td>
</tr>
<tr>
<td>417.212</td>
<td>Fe I</td>
<td>0.9 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>0.8 ± 0.2</td>
<td>1.2 ± 0.3</td>
<td>1.5 ± 0.2</td>
<td>...</td>
</tr>
<tr>
<td>417.353</td>
<td>Ti II</td>
<td>0.8 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>1.6 ± 0.3</td>
<td>1.1 ± 0.2</td>
<td></td>
</tr>
<tr>
<td>421.552</td>
<td>Sr II</td>
<td>1.1 ± 0.2</td>
<td>0.9 ± 0.3</td>
<td>...</td>
<td>1.3 ± 0.2</td>
<td>1.1 ± 0.3</td>
<td>...</td>
<td>2.9 ± 0.3</td>
<td>2.6 ± 0.3</td>
</tr>
<tr>
<td>422.673</td>
<td>Ca I</td>
<td>4.2 ± 0.2</td>
<td>5.1 ± 0.3</td>
<td>2.1 ± 0.6</td>
<td>2.7 ± 0.2</td>
<td>4.3 ± 0.2</td>
<td>3.3 ± 0.2</td>
<td>3.3 ± 0.3</td>
<td>4.8 ± 0.2</td>
</tr>
<tr>
<td>423.316</td>
<td>Fe II</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>0.9 ± 0.3</td>
<td>1.4 ± 0.3</td>
<td>1.4 ± 0.3</td>
<td>2.1 ± 0.4</td>
<td>1.8 ± 0.3</td>
</tr>
<tr>
<td>432.095</td>
<td>Ti II</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>1.3 ± 0.2</td>
<td>0.8 ± 0.2</td>
<td>1.6 ± 0.2</td>
<td>2.1 ± 0.2</td>
<td>...</td>
</tr>
<tr>
<td>434.047</td>
<td>H I</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>1.0 ± 0.2</td>
<td>...</td>
</tr>
<tr>
<td>437.482</td>
<td>Ti II</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>1.8 ± 0.3</td>
<td>1.5 ± 0.3</td>
<td>...</td>
</tr>
<tr>
<td>438.538</td>
<td>Fe II</td>
<td>0.8 ± 0.2</td>
<td>0.9 ± 0.2</td>
<td>...</td>
<td>1.0 ± 0.2</td>
<td>0.6 ± 0.2</td>
<td>0.6 ± 0.2</td>
<td>0.6 ± 0.2</td>
<td>0.8 ± 0.2</td>
</tr>
<tr>
<td>439.406</td>
<td>Ti II</td>
<td>...</td>
<td>1.2 ± 0.3</td>
<td>...</td>
<td>1.5 ± 0.2</td>
<td>...</td>
<td>1.0 ± 0.3</td>
<td>1.3 ± 0.3</td>
<td>1.9 ± 0.3</td>
</tr>
<tr>
<td>441.682</td>
<td>Fe II</td>
<td>0.9 ± 0.2</td>
<td>1.0 ± 0.2</td>
<td>...</td>
<td>1.3 ± 0.2</td>
<td>1.0 ± 0.2</td>
<td>0.7 ± 0.2</td>
<td>1.0 ± 0.2</td>
<td>1.1 ± 0.2</td>
</tr>
<tr>
<td>444.380</td>
<td>Ti II</td>
<td>0.8 ± 0.2</td>
<td>1.0 ± 0.3</td>
<td>...</td>
<td>1.0 ± 0.2</td>
<td>...</td>
<td>1.1 ± 0.2</td>
<td>1.6 ± 0.2</td>
<td>1.4 ± 0.2</td>
</tr>
<tr>
<td>444.456$^b$</td>
<td>Ti II</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td></td>
</tr>
<tr>
<td>446.849</td>
<td>Ti II</td>
<td>1.5 ± 0.2</td>
<td>1.5 ± 0.3</td>
<td>...</td>
<td>1.2 ± 0.2</td>
<td>1.1 ± 0.2</td>
<td>0.7 ± 0.2</td>
<td>1.5 ± 0.2</td>
<td>1.3 ± 0.2</td>
</tr>
<tr>
<td>448.832</td>
<td>Ti II</td>
<td>1.3 ± 0.2</td>
<td>1.5 ± 0.2</td>
<td>...</td>
<td>0.8 ± 0.2</td>
<td>...</td>
<td>0.5 ± 0.2</td>
<td>1.0 ± 0.2</td>
<td>2.0 ± 0.2</td>
</tr>
<tr>
<td>449.140</td>
<td>Fe II</td>
<td>1.1 ± 0.2</td>
<td>1.0 ± 0.3</td>
<td>...</td>
<td>0.9 ± 0.2</td>
<td>0.7 ± 0.2</td>
<td>1.3 ± 0.2</td>
<td>1.2 ± 0.2</td>
<td>1.8 ± 0.2</td>
</tr>
<tr>
<td>450.127</td>
<td>Ti II</td>
<td>1.3 ± 0.2</td>
<td>1.9 ± 0.3</td>
<td>...</td>
<td>1.5 ± 0.2</td>
<td>1.1 ± 0.3</td>
<td>...</td>
<td>1.8 ± 0.3</td>
<td>2.0 ± 0.3</td>
</tr>
<tr>
<td>450.828</td>
<td>Fe II</td>
<td>1.6 ± 0.2</td>
<td>1.3 ± 0.3</td>
<td>...</td>
<td>1.4 ± 0.2</td>
<td>1.2 ± 0.2</td>
<td>...</td>
<td>2.1 ± 0.2</td>
<td>2.3 ± 0.2</td>
</tr>
<tr>
<td>451.533</td>
<td>Fe II</td>
<td>1.3 ± 0.2</td>
<td>0.7 ± 0.2</td>
<td>...</td>
<td>1.1 ± 0.2</td>
<td>1.0 ± 0.2</td>
<td>0.7 ± 0.2</td>
<td>1.9 ± 0.2</td>
<td>2.0 ± 0.2</td>
</tr>
<tr>
<td>452.022</td>
<td>Fe II</td>
<td>1.0 ± 0.2</td>
<td>1.2 ± 0.2</td>
<td>...</td>
<td>0.8 ± 0.2</td>
<td>0.8 ± 0.2</td>
<td>...</td>
<td>1.8 ± 0.2</td>
<td>2.1 ± 0.2</td>
</tr>
<tr>
<td>452.263</td>
<td>Fe II</td>
<td>1.0 ± 0.2</td>
<td>0.9 ± 0.2</td>
<td>...</td>
<td>1.2 ± 0.2</td>
<td>1.2 ± 0.2</td>
<td>0.9 ± 0.2</td>
<td>2.1 ± 0.2</td>
<td>2.3 ± 0.2</td>
</tr>
<tr>
<td>453.396</td>
<td>Ti II</td>
<td>1.3 ± 0.2</td>
<td>1.0 ± 0.2</td>
<td>...</td>
<td>1.0 ± 0.2</td>
<td>0.9 ± 0.2</td>
<td>0.6 ± 0.2</td>
<td>1.8 ± 0.2</td>
<td>2.4 ± 0.2</td>
</tr>
<tr>
<td>454.152</td>
<td>Fe II</td>
<td>0.7 ± 0.2</td>
<td>1.2 ± 0.2</td>
<td>...</td>
<td>0.6 ± 0.2</td>
<td>0.7 ± 0.2</td>
<td>...</td>
<td>1.5 ± 0.2</td>
<td>2.2 ± 0.2</td>
</tr>
</tbody>
</table>

Continued on Next Page...
<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Species</th>
<th>54811&lt;sup&gt;a&lt;/sup&gt;</th>
<th>54877&lt;sup&gt;a&lt;/sup&gt;</th>
<th>54956</th>
<th>55086&lt;sup&gt;a&lt;/sup&gt;</th>
<th>55104&lt;sup&gt;a&lt;/sup&gt;</th>
<th>55115&lt;sup&gt;a&lt;/sup&gt;</th>
<th>55174&lt;sup&gt;a&lt;/sup&gt;</th>
<th>55225&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>EW (mA)</td>
<td>EW (mA)</td>
<td>EW (mA)</td>
<td>EW (mA)</td>
<td>EW (mA)</td>
<td>EW (mA)</td>
<td>EW (mA)</td>
<td>EW (mA)</td>
</tr>
<tr>
<td>455.864</td>
<td>Cr II</td>
<td>1.0 ± 0.2</td>
<td>1.1 ± 0.2</td>
<td>...</td>
<td>1.0 ± 0.2</td>
<td>0.9 ± 0.2</td>
<td>0.6 ± 0.2</td>
<td>1.7 ± 0.2</td>
<td>2.1 ± 0.2</td>
</tr>
<tr>
<td>456.376</td>
<td>Ti II</td>
<td>0.9 ± 0.2</td>
<td>0.9 ± 0.2</td>
<td>...</td>
<td>0.9 ± 0.2</td>
<td>1.3 ± 0.2</td>
<td>...</td>
<td>1.6 ± 0.2</td>
<td>2.0 ± 0.2</td>
</tr>
<tr>
<td>457.197</td>
<td>Ti II</td>
<td>0.9 ± 0.2</td>
<td>0.9 ± 0.2</td>
<td>...</td>
<td>0.9 ± 0.2</td>
<td>1.2 ± 0.2</td>
<td>0.7 ± 0.2</td>
<td>2.4 ± 0.2</td>
<td>2.1 ± 0.2</td>
</tr>
<tr>
<td>457.633</td>
<td>Fe II</td>
<td>0.7 ± 0.2</td>
<td>1.0 ± 0.2</td>
<td>...</td>
<td>1.0 ± 0.2</td>
<td>1.1 ± 0.2</td>
<td>0.6 ± 0.2</td>
<td>1.0 ± 0.2</td>
<td>1.7 ± 0.2</td>
</tr>
<tr>
<td>458.820</td>
<td>Cr II</td>
<td>1.3 ± 0.2</td>
<td>1.0 ± 0.3</td>
<td>...</td>
<td>1.3 ± 0.2</td>
<td>1.0 ± 0.2</td>
<td>0.8 ± 0.2</td>
<td>1.7 ± 0.2</td>
<td>1.8 ± 0.2</td>
</tr>
<tr>
<td>459.205</td>
<td>Cr II</td>
<td>0.7 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>0.6 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>0.8 ± 0.2</td>
<td>1.2 ± 0.2</td>
</tr>
<tr>
<td>461.876&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Fe I</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>461.881</td>
<td>Cr II</td>
<td>1.0 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>0.9 ± 0.2</td>
<td>0.9 ± 0.2</td>
<td>0.6 ± 0.2</td>
<td>1.3 ± 0.2</td>
<td>2.3 ± 0.2</td>
</tr>
<tr>
<td>462.051</td>
<td>Fe II</td>
<td>0.8 ± 0.2</td>
<td>0.8 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>1.3 ± 0.2</td>
<td>2.2 ± 0.2</td>
</tr>
<tr>
<td>462.929&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Ti II</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>462.933</td>
<td>Fe II</td>
<td>1.1 ± 0.2</td>
<td>1.1 ± 0.3</td>
<td>...</td>
<td>1.9 ± 0.2</td>
<td>0.8 ± 0.2</td>
<td>0.9 ± 0.2</td>
<td>2.1 ± 0.2</td>
<td>2.3 ± 0.2</td>
</tr>
<tr>
<td>467.041</td>
<td>Sc II</td>
<td>0.7 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>1.4 ± 0.2</td>
<td>2.0 ± 0.2</td>
</tr>
<tr>
<td>473.144</td>
<td>Fe II</td>
<td>0.9 ± 0.2</td>
<td>1.5 ± 0.3</td>
<td>...</td>
<td>0.9 ± 0.2</td>
<td>1.2 ± 0.2</td>
<td>0.9 ± 0.2</td>
<td>1.9 ± 0.2</td>
<td>1.9 ± 0.2</td>
</tr>
<tr>
<td>480.509</td>
<td>Ti II</td>
<td>1.7 ± 0.2</td>
<td>1.7 ± 0.2</td>
<td>...</td>
<td>1.2 ± 0.2</td>
<td>1.2 ± 0.2</td>
<td>0.9 ± 0.2</td>
<td>2.3 ± 0.2</td>
<td>2.5 ± 0.2</td>
</tr>
<tr>
<td>484.825</td>
<td>Cr II</td>
<td>0.9 ± 0.2</td>
<td>0.7 ± 0.2</td>
<td>...</td>
<td>1.1 ± 0.2</td>
<td>0.6 ± 0.2</td>
<td>...</td>
<td>0.9 ± 0.2</td>
<td>1.5 ± 0.2</td>
</tr>
<tr>
<td>485.136</td>
<td>H I</td>
<td>0.6 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>1.8 ± 0.2</td>
<td>0.8 ± 0.2</td>
<td>0.9 ± 0.2</td>
<td>1.4 ± 0.2</td>
<td>1.8 ± 0.2</td>
</tr>
<tr>
<td>487.649</td>
<td>Cr II</td>
<td>1.0 ± 0.2</td>
<td>1.0 ± 0.2</td>
<td>...</td>
<td>1.1 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>0.9 ± 0.2</td>
<td>1.7 ± 0.2</td>
</tr>
<tr>
<td>491.129</td>
<td>Ti II</td>
<td>0.8 ± 0.2</td>
<td>0.7 ± 0.2</td>
<td>...</td>
<td>0.7 ± 0.2</td>
<td>0.7 ± 0.2</td>
<td>0.6 ± 0.2</td>
<td>1.3 ± 0.2</td>
<td>2.0 ± 0.2</td>
</tr>
<tr>
<td>492.392</td>
<td>Fe II</td>
<td>1.4 ± 0.2</td>
<td>1.2 ± 0.3</td>
<td>...</td>
<td>2.3 ± 0.2</td>
<td>1.2 ± 0.2</td>
<td>1.5 ± 0.2</td>
<td>3.2 ± 0.2</td>
<td>2.2 ± 0.2</td>
</tr>
<tr>
<td>493.408</td>
<td>Ba II</td>
<td>0.8 ± 0.2</td>
<td>1.0 ± 0.3</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>1.1 ± 0.3</td>
<td>1.6 ± 0.2</td>
</tr>
<tr>
<td>495.760</td>
<td>Fe I</td>
<td>0.7 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>1.5 ± 0.3</td>
<td>1.8 ± 0.3</td>
</tr>
<tr>
<td>501.844</td>
<td>Fe II</td>
<td>1.2 ± 0.2</td>
<td>1.0 ± 0.3</td>
<td>...</td>
<td>2.3 ± 0.2</td>
<td>1.7 ± 0.2</td>
<td>1.5 ± 0.2</td>
<td>3.0 ± 0.2</td>
<td>2.2 ± 0.2</td>
</tr>
<tr>
<td>503.078</td>
<td>Fe I</td>
<td>0.9 ± 0.2</td>
<td>0.8 ± 0.2</td>
<td>...</td>
<td>0.8 ± 0.2</td>
<td>0.6 ± 0.2</td>
<td>...</td>
<td>1.8 ± 0.2</td>
<td>2.0 ± 0.2</td>
</tr>
<tr>
<td>512.916</td>
<td>Ti II</td>
<td>1.1 ± 0.2</td>
<td>0.6 ± 0.2</td>
<td>...</td>
<td>1.0 ± 0.2</td>
<td>0.8 ± 0.2</td>
<td>0.6 ± 0.2</td>
<td>1.4 ± 0.2</td>
<td>2.2 ± 0.2</td>
</tr>
<tr>
<td>516.732</td>
<td>Mg I</td>
<td>0.8 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>1.0 ± 0.2</td>
<td>1.4 ± 0.2</td>
</tr>
<tr>
<td>516.890&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Fe I</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>516.903</td>
<td>Fe II</td>
<td>1.7 ± 0.2</td>
<td>1.7 ± 0.2</td>
<td>...</td>
<td>1.4 ± 0.2</td>
<td>1.4 ± 0.2</td>
<td>1.6 ± 0.2</td>
<td>2.7 ± 0.2</td>
<td>2.4 ± 0.2</td>
</tr>
</tbody>
</table>

Continued on Next Page...
Table 5.4 – Continued

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Species</th>
<th>54811&lt;sup&gt;a&lt;/sup&gt;</th>
<th>54877&lt;sup&gt;a&lt;/sup&gt;</th>
<th>54956</th>
<th>55085&lt;sup&gt;a&lt;/sup&gt;</th>
<th>55104&lt;sup&gt;a&lt;/sup&gt;</th>
<th>55115&lt;sup&gt;a&lt;/sup&gt;</th>
<th>55174&lt;sup&gt;a&lt;/sup&gt;</th>
<th>55225&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>EW (mÅ)</td>
<td>EW (mÅ)</td>
<td>EW</td>
<td>EW (mÅ)</td>
<td>EW (mÅ)</td>
<td>EW (mÅ)</td>
<td>EW (mÅ)</td>
<td>EW (mÅ)</td>
</tr>
<tr>
<td>516.930&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Fe I</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>517.268</td>
<td>Mg I</td>
<td>0.6 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>0.6 ± 0.2</td>
<td>...</td>
<td>0.6 ± 0.2</td>
<td>1.7 ± 0.2</td>
<td>2.0 ± 0.2</td>
</tr>
<tr>
<td>518.360</td>
<td>Mg I</td>
<td>0.8 ± 0.2</td>
<td>0.8 ± 0.2</td>
<td>...</td>
<td>0.8 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>2.0 ± 0.2</td>
<td>1.7 ± 0.2</td>
</tr>
<tr>
<td>518.869</td>
<td>Ti II</td>
<td>0.8 ± 0.2</td>
<td>0.8 ± 0.2</td>
<td>...</td>
<td>1.1 ± 0.2</td>
<td>0.9 ± 0.2</td>
<td>0.7 ± 0.2</td>
<td>2.3 ± 0.2</td>
<td>2.0 ± 0.2</td>
</tr>
<tr>
<td>519.757</td>
<td>Fe II</td>
<td>0.9 ± 0.2</td>
<td>0.9 ± 0.2</td>
<td>...</td>
<td>1.6 ± 0.2</td>
<td>1.1 ± 0.2</td>
<td>1.3 ± 0.2</td>
<td>2.3 ± 0.2</td>
<td>2.1 ± 0.2</td>
</tr>
<tr>
<td>522.654</td>
<td>Ti II</td>
<td>0.6 ± 0.2</td>
<td>0.9 ± 0.2</td>
<td>...</td>
<td>1.0 ± 0.2</td>
<td>0.7 ± 0.2</td>
<td>0.8 ± 0.2</td>
<td>1.9 ± 0.2</td>
<td>2.3 ± 0.2</td>
</tr>
<tr>
<td>523.462</td>
<td>Fe II</td>
<td>1.3 ± 0.2</td>
<td>1.2 ± 0.2</td>
<td>1.5 ± 0.4</td>
<td>1.6 ± 0.2</td>
<td>1.6 ± 0.2</td>
<td>1.3 ± 0.2</td>
<td>2.8 ± 0.2</td>
<td>2.5 ± 0.2</td>
</tr>
<tr>
<td>523.736</td>
<td>Cr II</td>
<td>0.6 ± 0.2</td>
<td>0.8 ± 0.2</td>
<td>...</td>
<td>0.6 ± 0.2</td>
<td>1.0 ± 0.2</td>
<td>0.8 ± 0.2</td>
<td>1.3 ± 0.2</td>
<td>1.5 ± 0.2</td>
</tr>
<tr>
<td>525.496</td>
<td>Fe I</td>
<td>0.7 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>0.7 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>1.3 ± 0.2</td>
<td>1.6 ± 0.1</td>
</tr>
<tr>
<td>527.600</td>
<td>Fe II</td>
<td>1.3 ± 0.2</td>
<td>0.9 ± 0.3</td>
<td>...</td>
<td>1.6 ± 0.2</td>
<td>1.3 ± 0.2</td>
<td>1.0 ± 0.2</td>
<td>1.9 ± 0.3</td>
<td>2.3 ± 0.2</td>
</tr>
<tr>
<td>528.442</td>
<td>Fe I</td>
<td>1.0 ± 0.2</td>
<td>0.7 ± 0.2</td>
<td>...</td>
<td>0.6 ± 0.2</td>
<td>...</td>
<td>0.7 ± 0.2</td>
<td>1.4 ± 0.2</td>
<td>2.0 ± 0.2</td>
</tr>
<tr>
<td>531.678</td>
<td>Fe II</td>
<td>1.6 ± 0.2</td>
<td>1.0 ± 0.3</td>
<td>...</td>
<td>2.7 ± 0.2</td>
<td>1.9 ± 0.2</td>
<td>1.8 ± 0.2</td>
<td>3.0 ± 0.2</td>
<td>3.0 ± 0.2</td>
</tr>
<tr>
<td>533.679</td>
<td>Ti II</td>
<td>1.2 ± 0.2</td>
<td>1.2 ± 0.2</td>
<td>...</td>
<td>1.0 ± 0.2</td>
<td>0.7 ± 0.2</td>
<td>1.0 ± 0.2</td>
<td>1.6 ± 0.2</td>
<td>2.2 ± 0.2</td>
</tr>
<tr>
<td>536.275</td>
<td>Fe II</td>
<td>1.5 ± 0.2</td>
<td>1.2 ± 0.2</td>
<td>...</td>
<td>1.8 ± 0.2</td>
<td>1.6 ± 0.2</td>
<td>1.2 ± 0.2</td>
<td>2.2 ± 0.2</td>
<td>2.6 ± 0.2</td>
</tr>
<tr>
<td>538.102</td>
<td>Ti II</td>
<td>0.7 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>0.6 ± 0.2</td>
<td>...</td>
<td>0.6 ± 0.2</td>
<td>1.1 ± 0.2</td>
<td>1.4 ± 0.2</td>
</tr>
<tr>
<td>541.877</td>
<td>Ti II</td>
<td>...</td>
<td>0.7 ± 0.2</td>
<td>...</td>
<td>0.6 ± 0.2</td>
<td>0.6 ± 0.2</td>
<td>0.6 ± 0.2</td>
<td>0.8 ± 0.2</td>
<td>1.3 ± 0.2</td>
</tr>
<tr>
<td>552.679</td>
<td>Sc II</td>
<td>1.1 ± 0.2</td>
<td>0.8 ± 0.2</td>
<td>...</td>
<td>0.7 ± 0.2</td>
<td>0.9 ± 0.2</td>
<td>0.6 ± 0.2</td>
<td>2.0 ± 0.2</td>
<td>2.6 ± 0.2</td>
</tr>
<tr>
<td>553.484</td>
<td>Fe II</td>
<td>1.1 ± 0.2</td>
<td>1.1 ± 0.2</td>
<td>...</td>
<td>1.3 ± 0.2</td>
<td>1.0 ± 0.2</td>
<td>1.2 ± 0.2</td>
<td>2.5 ± 0.2</td>
<td>2.2 ± 0.2</td>
</tr>
<tr>
<td>565.791</td>
<td>Sc II</td>
<td>0.7 ± 0.2</td>
<td>0.7 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>1.3 ± 0.2</td>
<td>1.7 ± 0.2</td>
</tr>
<tr>
<td>623.838</td>
<td>Fe II</td>
<td>0.9 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>0.7 ± 0.2</td>
<td>...</td>
<td>0.6 ± 0.2</td>
<td>1.3 ± 0.2</td>
<td>1.7 ± 0.2</td>
</tr>
<tr>
<td>624.756</td>
<td>Fe II</td>
<td>0.9 ± 0.2</td>
<td>1.1 ± 0.2</td>
<td>...</td>
<td>1.3 ± 0.2</td>
<td>1.0 ± 0.2</td>
<td>1.2 ± 0.2</td>
<td>2.1 ± 0.2</td>
<td>2.4 ± 0.2</td>
</tr>
<tr>
<td>641.693</td>
<td>Fe II</td>
<td>0.8 ± 0.2</td>
<td>1.0 ± 0.2</td>
<td>...</td>
<td>0.7 ± 0.2</td>
<td>0.8 ± 0.2</td>
<td>...</td>
<td>1.0 ± 0.2</td>
<td>1.4 ± 0.2</td>
</tr>
<tr>
<td>643.268</td>
<td>Fe II</td>
<td>0.8 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>0.7 ± 0.2</td>
<td>0.7 ± 0.2</td>
<td>0.6 ± 0.2</td>
<td>1.2 ± 0.2</td>
<td>1.6 ± 0.2</td>
</tr>
<tr>
<td>645.638</td>
<td>Fe II</td>
<td>1.2 ± 0.2</td>
<td>0.8 ± 0.2</td>
<td>...</td>
<td>1.8 ± 0.2</td>
<td>1.4 ± 0.2</td>
<td>1.3 ± 0.2</td>
<td>2.6 ± 0.2</td>
<td>2.7 ± 0.2</td>
</tr>
<tr>
<td>651.608</td>
<td>Fe II</td>
<td>0.6 ± 0.2</td>
<td>0.8 ± 0.2</td>
<td>1.3 ± 0.4</td>
<td>1.0 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>1.4 ± 0.2</td>
<td>2.0 ± 0.2</td>
</tr>
<tr>
<td>656.220</td>
<td>Fe II</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>656.280</td>
<td>H I</td>
<td>4.2 ± 0.3</td>
<td>3.0 ± 0.5</td>
<td>0.9 ± 0.9</td>
<td>6.9 ± 0.4</td>
<td>7.2 ± 0.4</td>
<td>5.7 ± 0.4</td>
<td>8.8 ± 0.5</td>
<td>7.3 ± 0.4</td>
</tr>
</tbody>
</table>

Continued on Next Page...
### Table 5.4 – Continued

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Species</th>
<th>54811&lt;sup&gt;a&lt;/sup&gt;</th>
<th>54877&lt;sup&gt;a&lt;/sup&gt;</th>
<th>54956</th>
<th>55086&lt;sup&gt;a&lt;/sup&gt;</th>
<th>55104&lt;sup&gt;a&lt;/sup&gt;</th>
<th>55115&lt;sup&gt;a&lt;/sup&gt;</th>
<th>55174&lt;sup&gt;a&lt;/sup&gt;</th>
<th>55225&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>769.896</td>
<td>K I</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>849.802</td>
<td>Ca II</td>
<td>1.4 ± 0.3</td>
<td>...</td>
<td>...</td>
<td>2.2 ± 0.3</td>
<td>1.8 ± 0.4</td>
<td>1.7 ± 0.4</td>
<td>3.1 ± 0.4</td>
<td>3.0 ± 0.4</td>
</tr>
<tr>
<td>854.209</td>
<td>Ca II</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>1.7 ± 0.3</td>
<td>...</td>
<td>2.8 ± 0.5</td>
<td>2.0 ± 0.5</td>
<td></td>
</tr>
<tr>
<td>866.214</td>
<td>Ca II</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>1.8 ± 0.2</td>
<td>1.4 ± 0.2</td>
<td>...</td>
<td>3.1 ± 0.3</td>
<td>1.5 ± 0.2</td>
</tr>
</tbody>
</table>

**Note:** This table contains polarized flux equivalent widths calculated using the range of wavelengths given for EW Meow (Table 5.2).

<sup>a</sup>Epoch–binned data (see Table 5.1).

<sup>b</sup>Blend.
Table 5.5: Polarized flux EW: Mid–eclipse to post–eclipse

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Species</th>
<th>55264 EW (mA)</th>
<th>55414° EW (mA)</th>
<th>55489° EW (mA)</th>
<th>55518° EW (mA)</th>
<th>55525° EW (mA)</th>
<th>55550 EW (mA)</th>
<th>55791 EW (mA)</th>
<th>55882° EW (mA)</th>
<th>55944° EW (mA)</th>
<th>56271 EW (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>407.771</td>
<td>Sr II</td>
<td>...</td>
<td>3.7 ± 0.4</td>
<td>3.1 ± 0.3</td>
<td>2.9 ± 0.4</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>410.173</td>
<td>H I</td>
<td>1.1 ± 0.3</td>
<td>1.2 ± 0.3</td>
<td>1.6 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>417.212</td>
<td>Fe I</td>
<td>1.8 ± 0.3</td>
<td>1.1 ± 0.3</td>
<td>1.8 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>417.353</td>
<td>Ti II</td>
<td>1.6 ± 0.3</td>
<td>1.1 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>421.552</td>
<td>Sr II</td>
<td>2.1 ± 0.4</td>
<td>3.2 ± 0.3</td>
<td>4.1 ± 0.3</td>
<td>2.9 ± 0.2</td>
<td>2.3 ± 0.3</td>
<td>2.1 ± 0.7</td>
<td>1.8 ± 0.5</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>422.673</td>
<td>Ca I</td>
<td>6.5 ± 0.4</td>
<td>5.7 ± 0.3</td>
<td>6.0 ± 0.3</td>
<td>9.5 ± 0.2</td>
<td>8.5 ± 0.3</td>
<td>4.3 ± 0.6</td>
<td>3.3 ± 0.4</td>
<td>2.7 ± 0.4</td>
<td>2.6 ± 0.3</td>
<td>...</td>
</tr>
<tr>
<td>423.316</td>
<td>Fe II</td>
<td>2.2 ± 0.5</td>
<td>1.6 ± 0.3</td>
<td>3.1 ± 0.4</td>
<td>2.6 ± 0.3</td>
<td>2.0 ± 0.3</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>432.095</td>
<td>Ti II</td>
<td>1.1 ± 0.3</td>
<td>2.5 ± 0.2</td>
<td>3.7 ± 0.3</td>
<td>2.8 ± 0.2</td>
<td>1.9 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>0.8 ± 0.2</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>434.047</td>
<td>H I</td>
<td>...</td>
<td>0.9 ± 0.3</td>
<td>0.6 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>437.482</td>
<td>Ti II</td>
<td>1.6 ± 0.4</td>
<td>1.8 ± 0.3</td>
<td>3.0 ± 0.3</td>
<td>2.4 ± 0.2</td>
<td>2.0 ± 0.3</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>438.538</td>
<td>Fe II</td>
<td>2.0 ± 0.2</td>
<td>1.6 ± 0.2</td>
<td>1.8 ± 0.1</td>
<td>1.5 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>439.406</td>
<td>Ti II</td>
<td>2.7 ± 0.3</td>
<td>3.5 ± 0.3</td>
<td>2.9 ± 0.2</td>
<td>2.1 ± 0.3</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>441.682</td>
<td>Fe II</td>
<td>2.4 ± 0.2</td>
<td>2.1 ± 0.2</td>
<td>2.0 ± 0.2</td>
<td>1.8 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>0.9 ± 0.3</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>444.380</td>
<td>Ti II</td>
<td>1.4 ± 0.3</td>
<td>2.0 ± 0.2</td>
<td>3.2 ± 0.3</td>
<td>2.3 ± 0.2</td>
<td>1.7 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>444.456b</td>
<td>Ti II</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>446.849</td>
<td>Ti II</td>
<td>1.1 ± 0.3</td>
<td>2.5 ± 0.2</td>
<td>3.4 ± 0.3</td>
<td>2.4 ± 0.2</td>
<td>2.3 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>0.9 ± 0.2</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>448.832</td>
<td>Ti II</td>
<td>1.2 ± 0.3</td>
<td>3.1 ± 0.2</td>
<td>2.9 ± 0.3</td>
<td>2.7 ± 0.2</td>
<td>2.4 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>1.4 ± 0.3</td>
<td>0.8 ± 0.2</td>
<td>...</td>
</tr>
<tr>
<td>449.140</td>
<td>Fe II</td>
<td>1.2 ± 0.3</td>
<td>3.1 ± 0.2</td>
<td>3.4 ± 0.3</td>
<td>2.6 ± 0.2</td>
<td>2.1 ± 0.2</td>
<td>1.5 ± 0.5</td>
<td>0.9 ± 0.3</td>
<td>...</td>
<td>0.7 ± 0.2</td>
<td>...</td>
</tr>
<tr>
<td>450.127</td>
<td>Ti II</td>
<td>2.2 ± 0.4</td>
<td>2.6 ± 0.3</td>
<td>4.0 ± 0.3</td>
<td>2.9 ± 0.2</td>
<td>3.0 ± 0.3</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>450.828</td>
<td>Fe II</td>
<td>1.2 ± 0.4</td>
<td>2.7 ± 0.2</td>
<td>4.2 ± 0.3</td>
<td>3.2 ± 0.2</td>
<td>2.8 ± 0.2</td>
<td>2.3 ± 0.5</td>
<td>...</td>
<td>1.1 ± 0.3</td>
<td>0.9 ± 0.3</td>
<td>...</td>
</tr>
<tr>
<td>451.533</td>
<td>Fe II</td>
<td>1.4 ± 0.3</td>
<td>2.9 ± 0.2</td>
<td>3.6 ± 0.3</td>
<td>2.4 ± 0.2</td>
<td>2.1 ± 0.2</td>
<td>...</td>
<td>1.5 ± 0.3</td>
<td>...</td>
<td>0.8 ± 0.2</td>
<td>...</td>
</tr>
<tr>
<td>452.022</td>
<td>Fe II</td>
<td>1.0 ± 0.3</td>
<td>2.4 ± 0.2</td>
<td>3.0 ± 0.2</td>
<td>2.2 ± 0.2</td>
<td>1.6 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>0.9 ± 0.2</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>452.263</td>
<td>Fe II</td>
<td>0.9 ± 0.3</td>
<td>2.4 ± 0.2</td>
<td>3.9 ± 0.2</td>
<td>2.6 ± 0.2</td>
<td>1.8 ± 0.2</td>
<td>...</td>
<td>0.9 ± 0.3</td>
<td>...</td>
<td>0.6 ± 0.2</td>
<td>...</td>
</tr>
<tr>
<td>453.396</td>
<td>Ti II</td>
<td>1.6 ± 0.3</td>
<td>2.5 ± 0.2</td>
<td>3.9 ± 0.2</td>
<td>2.5 ± 0.2</td>
<td>2.5 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>454.152</td>
<td>Fe II</td>
<td>1.3 ± 0.3</td>
<td>2.6 ± 0.2</td>
<td>3.3 ± 0.2</td>
<td>1.9 ± 0.2</td>
<td>1.7 ± 0.2</td>
<td>1.5 ± 0.5</td>
<td>1.3 ± 0.3</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>455.864</td>
<td>Cr II</td>
<td>1.0 ± 0.3</td>
<td>2.4 ± 0.2</td>
<td>3.2 ± 0.2</td>
<td>2.1 ± 0.2</td>
<td>1.6 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>0.8 ± 0.2</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>456.376</td>
<td>Ti II</td>
<td>1.0 ± 0.3</td>
<td>2.5 ± 0.2</td>
<td>3.1 ± 0.2</td>
<td>2.2 ± 0.2</td>
<td>2.3 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>1.0 ± 0.2</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>457.197</td>
<td>Ti II</td>
<td>1.5 ± 0.3</td>
<td>1.9 ± 0.2</td>
<td>3.8 ± 0.2</td>
<td>2.7 ± 0.2</td>
<td>2.4 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>0.9 ± 0.2</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

Continued on Next Page...
Table 5.5 – Continued

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Species</th>
<th>55264</th>
<th>55414&lt;sup&gt;a&lt;/sup&gt;</th>
<th>55489&lt;sup&gt;a&lt;/sup&gt;</th>
<th>55618&lt;sup&gt;a&lt;/sup&gt;</th>
<th>55525</th>
<th>55550</th>
<th>55791</th>
<th>55882&lt;sup&gt;a&lt;/sup&gt;</th>
<th>55944&lt;sup&gt;a&lt;/sup&gt;</th>
<th>56271</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>EW</td>
<td>EW</td>
<td>EW</td>
<td>EW</td>
<td>EW</td>
<td>EW</td>
<td>EW</td>
<td>EW</td>
<td>EW</td>
<td>EW</td>
</tr>
</tbody>
</table>

457.633 Fe II 0.9 ± 0.3 2.6 ± 0.2 2.8 ± 0.3 1.8 ± 0.2 1.3 ± 0.2 1.9 ± 0.5 1.0 ± 0.3 ... ... ...
458.820 Cr II ... 2.7 ± 0.2 3.4 ± 0.3 2.8 ± 0.2 1.9 ± 0.2 ... ... ... 1.3 ± 0.2 2.0 ± 0.4 ...
459.205 Cr II 2.0 ± 0.2 2.1 ± 0.3 1.7 ± 0.2 1.3 ± 0.2 ... 0.9 ± 0.3 ... ...
461.876<sup>b</sup> Fe I ... ... ... ... ... ... ... ...
461.881 Cr II 0.9 ± 0.3 2.7 ± 0.2 3.4 ± 0.2 2.4 ± 0.2 1.6 ± 0.2 1.5 ± 0.4 0.9 ± 0.3 ... 1.3 ± 0.2 ...
462.051 Fe II ... 2.2 ± 0.2 2.5 ± 0.2 2.1 ± 0.2 1.5 ± 0.2 1.6 ± 0.4 ... ... ...
462.929<sup>b</sup> Ti II ... ... ... ... ... ... ... ...
462.933 Fe II 1.0 ± 0.3 2.9 ± 0.2 3.7 ± 0.3 3.2 ± 0.2 2.6 ± 0.2 1.6 ± 0.5 ... ... 1.7 ± 0.2 ...
467.041 Sc II 1.4 ± 0.3 3.0 ± 0.2 3.0 ± 0.3 1.9 ± 0.2 1.6 ± 0.2 ... ... ... ...
473.144 Fe II 1.2 ± 0.3 2.7 ± 0.2 3.4 ± 0.3 2.4 ± 0.2 2.1 ± 0.2 2.2 ± 0.5 1.1 ± 0.3 1.1 ± 0.3 ...
480.509 Ti II 1.6 ± 0.3 3.2 ± 0.2 3.4 ± 0.3 2.8 ± 0.2 2.1 ± 0.2 2.1 ± 0.5 1.2 ± 0.3 0.9 ± 0.3 0.9 ± 0.2 1.4 ± 0.4 ...
484.825 Cr II 1.0 ± 0.3 2.1 ± 0.2 2.7 ± 0.2 2.0 ± 0.2 1.0 ± 0.2 ... 0.6 ± 0.3 1.2 ± 0.3 0.7 ± 0.2 ...
486.135 H I ... 2.7 ± 0.2 2.2 ± 0.2 1.7 ± 0.2 1.1 ± 0.2 ... ... ... ...
487.649 Cr II 1.1 ± 0.3 2.5 ± 0.2 2.6 ± 0.2 2.2 ± 0.2 1.3 ± 0.2 1.5 ± 0.4 0.9 ± 0.3 1.1 ± 0.2 ... 1.0 ± 0.3 ...
491.120 Ti II 1.1 ± 0.3 2.3 ± 0.2 2.7 ± 0.2 1.6 ± 0.2 1.0 ± 0.2 1.2 ± 0.4 0.9 ± 0.3 1.0 ± 0.3 1.1 ± 0.2 1.2 ± 0.4 ...
492.392 Fe II ... 1.7 ± 0.2 4.1 ± 0.3 3.9 ± 0.2 3.2 ± 0.2 ... ... ... 1.2 ± 0.3 ...
493.408 Ba II 1.2 ± 0.4 2.4 ± 0.2 2.5 ± 0.3 2.0 ± 0.2 1.4 ± 0.2 ... ... ... 1.1 ± 0.3 ...
495.760 Fe I ... 2.3 ± 0.3 2.3 ± 0.3 1.3 ± 0.2 0.9 ± 0.3 ... ... ... ...
501.844 Fe II ... 2.1 ± 0.2 3.5 ± 0.3 3.3 ± 0.2 2.9 ± 0.2 ... ... ... ...
503.078 Fe I 0.9 ± 0.3 2.8 ± 0.2 3.1 ± 0.2 2.2 ± 0.2 1.4 ± 0.2 ... ... ... 0.8 ± 0.2 ...
512.916 Ti II 1.8 ± 0.2 2.8 ± 0.2 2.8 ± 0.2 2.4 ± 0.2 1.5 ± 0.2 1.2 ± 0.4 0.8 ± 0.2 0.8 ± 0.2 0.7 ± 0.2 ...
516.732 Mg I 0.6 ± 0.2 1.7 ± 0.2 1.5 ± 0.2 1.7 ± 0.2 0.9 ± 0.2 ... 0.7 ± 0.2 0.6 ± 0.2 ...
516.890<sup>b</sup> Fe I ... ... ... ... ... ... ... ...
516.903 Fe II 0.8 ± 0.2 1.7 ± 0.2 2.5 ± 0.2 3.1 ± 0.2 2.4 ± 0.2 ... ... 1.1 ± 0.2 1.1 ± 0.2 ...
516.930<sup>b</sup> Fe I ... ... ... ... ... ... ... ...
517.268 Mg I ... 2.6 ± 0.2 2.3 ± 0.3 2.3 ± 0.2 1.4 ± 0.2 ... ... ... ...
518.360 Mg I ... 2.7 ± 0.2 2.7 ± 0.2 2.7 ± 0.2 2.2 ± 0.2 ... 1.0 ± 0.3 ... 0.7 ± 0.2 ...
518.869 Ti II ... 2.7 ± 0.2 3.1 ± 0.2 2.4 ± 0.2 1.8 ± 0.2 ... 1.1 ± 0.3 0.7 ± 0.2 0.7 ± 0.2 ...
519.757 Fe II ... 2.9 ± 0.2 3.0 ± 0.2 3.0 ± 0.2 2.3 ± 0.2 ... 1.2 ± 0.3 ... 0.8 ± 0.2 ...

Continued on Next Page...
<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Species</th>
<th>55264</th>
<th>55414*</th>
<th>55489*</th>
<th>55518*</th>
<th>55525*</th>
<th>55550</th>
<th>55791</th>
<th>55882*</th>
<th>55944*</th>
<th>56271</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>EW</td>
<td>EW</td>
<td>EW</td>
<td>EW</td>
<td>EW</td>
<td>EW</td>
<td>EW</td>
<td>EW</td>
<td>EW</td>
<td>EW</td>
</tr>
<tr>
<td>522.654</td>
<td>Ti II</td>
<td>1.4 ± 0.3</td>
<td>2.5 ± 0.2</td>
<td>2.7 ± 0.2</td>
<td>2.4 ± 0.2</td>
<td>1.7 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>523.462</td>
<td>Fe II</td>
<td>1.1 ± 0.3</td>
<td>2.6 ± 0.2</td>
<td>3.5 ± 0.2</td>
<td>3.4 ± 0.2</td>
<td>2.7 ± 0.2</td>
<td>...</td>
<td>1.2 ± 0.3</td>
<td>...</td>
<td>1.6 ± 0.2</td>
<td>...</td>
</tr>
<tr>
<td>525.496</td>
<td>Cr II</td>
<td>1.0 ± 0.3</td>
<td>2.4 ± 0.2</td>
<td>2.4 ± 0.2</td>
<td>1.8 ± 0.2</td>
<td>1.9 ± 0.2</td>
<td>...</td>
<td>1.4 ± 0.3</td>
<td>...</td>
<td>0.8 ± 0.2</td>
<td>...</td>
</tr>
<tr>
<td>527.600</td>
<td>Fe II</td>
<td>0.8 ± 0.2</td>
<td>2.2 ± 0.2</td>
<td>2.5 ± 0.2</td>
<td>1.5 ± 0.2</td>
<td>1.0 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>0.9 ± 0.2</td>
<td>1.1 ± 0.3</td>
<td>...</td>
</tr>
<tr>
<td>528.442</td>
<td>Fe I</td>
<td>...</td>
<td>2.6 ± 0.2</td>
<td>3.0 ± 0.3</td>
<td>3.1 ± 0.2</td>
<td>2.3 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>531.678</td>
<td>Fe II</td>
<td>0.9 ± 0.3</td>
<td>2.8 ± 0.2</td>
<td>2.8 ± 0.2</td>
<td>2.5 ± 0.2</td>
<td>1.3 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>0.8 ± 0.2</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>533.679</td>
<td>Ti II</td>
<td>1.1 ± 0.3</td>
<td>2.9 ± 0.2</td>
<td>3.9 ± 0.3</td>
<td>3.7 ± 0.2</td>
<td>2.8 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>1.0 ± 0.3</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>536.275</td>
<td>Fe II</td>
<td>1.2 ± 0.3</td>
<td>3.2 ± 0.2</td>
<td>3.8 ± 0.2</td>
<td>3.1 ± 0.2</td>
<td>2.7 ± 0.2</td>
<td>1.7 ± 0.4</td>
<td>...</td>
<td>1.2 ± 0.2</td>
<td>...</td>
<td>0.9 ± 0.3</td>
</tr>
<tr>
<td>538.102</td>
<td>Ti II</td>
<td>...</td>
<td>2.4 ± 0.2</td>
<td>2.9 ± 0.2</td>
<td>2.1 ± 0.2</td>
<td>1.1 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>541.877</td>
<td>Ti II</td>
<td>0.9 ± 0.3</td>
<td>1.5 ± 0.2</td>
<td>1.7 ± 0.2</td>
<td>1.4 ± 0.2</td>
<td>1.0 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>552.679</td>
<td>Sc II</td>
<td>1.1 ± 0.3</td>
<td>2.9 ± 0.2</td>
<td>3.1 ± 0.2</td>
<td>2.5 ± 0.2</td>
<td>1.8 ± 0.2</td>
<td>1.2 ± 0.4</td>
<td>1.3 ± 0.2</td>
<td>...</td>
<td>0.9 ± 0.2</td>
<td>...</td>
</tr>
<tr>
<td>553.484</td>
<td>Fe II</td>
<td>1.3 ± 0.3</td>
<td>3.0 ± 0.2</td>
<td>3.5 ± 0.2</td>
<td>2.8 ± 0.2</td>
<td>2.2 ± 0.2</td>
<td>2.1 ± 0.4</td>
<td>0.9 ± 0.3</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>565.791</td>
<td>Sc II</td>
<td>1.3 ± 0.3</td>
<td>2.0 ± 0.2</td>
<td>2.8 ± 0.2</td>
<td>1.6 ± 0.2</td>
<td>1.6 ± 0.2</td>
<td>...</td>
<td>1.1 ± 0.3</td>
<td>...</td>
<td>0.9 ± 0.3</td>
<td>...</td>
</tr>
<tr>
<td>623.838</td>
<td>Fe II</td>
<td>...</td>
<td>1.9 ± 0.2</td>
<td>1.6 ± 0.2</td>
<td>1.3 ± 0.2</td>
<td>0.8 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>0.8 ± 0.2</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>624.756</td>
<td>Fe II</td>
<td>1.3 ± 0.3</td>
<td>2.9 ± 0.2</td>
<td>2.6 ± 0.2</td>
<td>2.5 ± 0.2</td>
<td>1.7 ± 0.2</td>
<td>1.5 ± 0.4</td>
<td>1.1 ± 0.3</td>
<td>...</td>
<td>0.8 ± 0.2</td>
<td>...</td>
</tr>
<tr>
<td>641.693</td>
<td>Fe II</td>
<td>1.5 ± 0.3</td>
<td>1.5 ± 0.2</td>
<td>2.1 ± 0.2</td>
<td>1.8 ± 0.2</td>
<td>1.7 ± 0.2</td>
<td>...</td>
<td>0.9 ± 0.3</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>643.268</td>
<td>Fe II</td>
<td>1.0 ± 0.3</td>
<td>2.1 ± 0.2</td>
<td>1.7 ± 0.2</td>
<td>1.4 ± 0.2</td>
<td>1.2 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>645.638</td>
<td>Fe II</td>
<td>1.8 ± 0.3</td>
<td>3.8 ± 0.2</td>
<td>3.8 ± 0.2</td>
<td>3.1 ± 0.2</td>
<td>2.4 ± 0.2</td>
<td>2.2 ± 0.4</td>
<td>0.9 ± 0.3</td>
<td>...</td>
<td>1.1 ± 0.2</td>
<td>...</td>
</tr>
<tr>
<td>651.608</td>
<td>Fe II</td>
<td>1.0 ± 0.3</td>
<td>2.5 ± 0.2</td>
<td>2.4 ± 0.2</td>
<td>2.1 ± 0.2</td>
<td>1.1 ± 0.2</td>
<td>1.5 ± 0.5</td>
<td>...</td>
<td>...</td>
<td>1.2 ± 0.4</td>
<td>...</td>
</tr>
<tr>
<td>656.280</td>
<td>H I</td>
<td>...</td>
<td>8.4 ± 0.4</td>
<td>6.3 ± 0.4</td>
<td>7.3 ± 0.3</td>
<td>8.2 ± 0.4</td>
<td>7.2 ± 0.9</td>
<td>2.7 ± 0.6</td>
<td>2.0 ± 0.6</td>
<td>1.5 ± 0.5</td>
<td>1.9 ± 0.8</td>
</tr>
<tr>
<td>769.896</td>
<td>K I</td>
<td>1.3 ± 0.4</td>
<td>1.4 ± 0.3</td>
<td>1.3 ± 0.3</td>
<td>1.3 ± 0.2</td>
<td>1.9 ± 0.3</td>
<td>1.7 ± 0.5</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>849.802</td>
<td>Ca II</td>
<td>...</td>
<td>1.1 ± 0.4</td>
<td>4.2 ± 0.4</td>
<td>2.2 ± 0.3</td>
<td>2.5 ± 0.4</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

Continued on Next Page...
<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Species</th>
<th>55264</th>
<th>55414&lt;sup&gt;a&lt;/sup&gt;</th>
<th>55489&lt;sup&gt;a&lt;/sup&gt;</th>
<th>55518&lt;sup&gt;a&lt;/sup&gt;</th>
<th>55525&lt;sup&gt;a&lt;/sup&gt;</th>
<th>55550</th>
<th>55791</th>
<th>55882&lt;sup&gt;a&lt;/sup&gt;</th>
<th>55944&lt;sup&gt;a&lt;/sup&gt;</th>
<th>56271</th>
</tr>
</thead>
<tbody>
<tr>
<td>854.209</td>
<td>Ca II</td>
<td>⋯</td>
<td>1.0 ± 0.4</td>
<td>⋯</td>
<td>2.0 ± 0.3</td>
<td>2.5 ± 0.4</td>
<td>⋯</td>
<td>⋯</td>
<td>⋯</td>
<td>⋯</td>
<td>⋯</td>
</tr>
<tr>
<td>866.214</td>
<td>Ca II</td>
<td>⋯</td>
<td>⋯</td>
<td>1.5 ± 0.2</td>
<td>1.2 ± 0.2</td>
<td>⋯</td>
<td>⋯</td>
<td>⋯</td>
<td>⋯</td>
<td>⋯</td>
<td>⋯</td>
</tr>
</tbody>
</table>

**Note:** This table contains polarized flux equivalent widths calculated using the range of wavelengths given for EW (Table 5.2).

<sup>a</sup>Epoch–binned data (see Table 5.1).

<sup>b</sup>Blend.
Table 5.6: Atomic transitions

<table>
<thead>
<tr>
<th>Spec</th>
<th>Wavel (nm)</th>
<th>Lower level</th>
<th>Upper level</th>
<th>$J_i$</th>
<th>$J_k$</th>
<th>$E_i$ (eV)</th>
<th>$E_k$ (eV)</th>
<th>$A_{ki}$ (s$^{-1}$)</th>
<th>$f_{ik}$</th>
<th>log(gf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca II</td>
<td>849.802</td>
<td>3p6.3d</td>
<td>2D</td>
<td>3/2</td>
<td>3p6.4p</td>
<td>2P*</td>
<td>3/2</td>
<td>1.69</td>
<td>1.11E+06</td>
<td>1.20E-02</td>
</tr>
<tr>
<td></td>
<td>854.209</td>
<td>3p6.3d</td>
<td>2D</td>
<td>5/2</td>
<td>3p6.4p</td>
<td>2P*</td>
<td>3/2</td>
<td>1.70</td>
<td>9.90E+06</td>
<td>7.20E-02</td>
</tr>
<tr>
<td></td>
<td>866.214</td>
<td>3p6.3d</td>
<td>2D</td>
<td>3/2</td>
<td>3p6.4p</td>
<td>2P*</td>
<td>1/2</td>
<td>1.69</td>
<td>1.06E+07</td>
<td>5.97E-02</td>
</tr>
<tr>
<td>Sc II</td>
<td>565.791</td>
<td>3p6.3d.4p</td>
<td>3P</td>
<td>2</td>
<td>3p6.3d.4p</td>
<td>3P*</td>
<td>2</td>
<td>1.51</td>
<td>1.04E+07</td>
<td>5.00E-02</td>
</tr>
<tr>
<td>Ti II</td>
<td>417.353</td>
<td>3d2.(1D).4s</td>
<td>a 2D</td>
<td>5/2</td>
<td>3d2.(3F).4p</td>
<td>z 4D*</td>
<td>5/2</td>
<td>1.08</td>
<td>8.35E+05</td>
<td>2.18E-03</td>
</tr>
<tr>
<td></td>
<td>432.095</td>
<td>3d3</td>
<td>a 4P</td>
<td>3/2</td>
<td>3d2.(3F).4p</td>
<td>z 4D*</td>
<td>1/2</td>
<td>1.16</td>
<td>2.81E+06</td>
<td>3.93E-03</td>
</tr>
<tr>
<td></td>
<td>437.482</td>
<td>3d2.(3P).4s</td>
<td>b 2P</td>
<td>3/2</td>
<td>3d2.(1D).4p</td>
<td>y 2D*</td>
<td>5/2</td>
<td>2.06</td>
<td>1.41E+06</td>
<td>6.07E-03</td>
</tr>
<tr>
<td></td>
<td>439.406</td>
<td>3d3</td>
<td>a 2P</td>
<td>1/2</td>
<td>3d2.(3F).4p</td>
<td>z 4D*</td>
<td>3/2</td>
<td>1.22</td>
<td>1.42E+06</td>
<td>8.23E-03</td>
</tr>
<tr>
<td></td>
<td>448.832</td>
<td>3d4.5s</td>
<td>c 2D</td>
<td>5/2</td>
<td>3d2.(1G).4p</td>
<td>x 2F*</td>
<td>7/2</td>
<td>3.12</td>
<td>1.28E+07</td>
<td>5.16E-02</td>
</tr>
<tr>
<td></td>
<td>457.197</td>
<td>3d3</td>
<td>a 2H</td>
<td>9/2</td>
<td>3d2.(3F).4p</td>
<td>z 2G*</td>
<td>7/2</td>
<td>1.57</td>
<td>1.92E+07</td>
<td>4.82E-02</td>
</tr>
<tr>
<td></td>
<td>491.120</td>
<td>3d4.5s</td>
<td>c 2D</td>
<td>5/2</td>
<td>3d2.(3P).4p</td>
<td>y 2P*</td>
<td>3/2</td>
<td>3.12</td>
<td>1.70E+07</td>
<td>4.10E-02</td>
</tr>
<tr>
<td></td>
<td>518.869</td>
<td>3d3</td>
<td>b 2D</td>
<td>5/2</td>
<td>3d2.(3F).4p</td>
<td>z 2D*</td>
<td>5/2</td>
<td>1.58</td>
<td>2.50E+06</td>
<td>1.00E-02</td>
</tr>
<tr>
<td></td>
<td>522.654</td>
<td>3d3</td>
<td>b 2D</td>
<td>3/2</td>
<td>3d2.(3F).4p</td>
<td>z 2D*</td>
<td>3/2</td>
<td>1.57</td>
<td>3.10E+06</td>
<td>1.30E-02</td>
</tr>
<tr>
<td></td>
<td>533.679</td>
<td>3d3</td>
<td>b 2D</td>
<td>5/2</td>
<td>3d2.(3F).4p</td>
<td>z 2F*</td>
<td>7/2</td>
<td>1.58</td>
<td>5.80E+05</td>
<td>3.30E-03</td>
</tr>
<tr>
<td></td>
<td>538.102</td>
<td>3d3</td>
<td>b 2D</td>
<td>3/2</td>
<td>3d2.(3F).4p</td>
<td>z 2F*</td>
<td>5/2</td>
<td>1.57</td>
<td>4.60E+05</td>
<td>3.00E-03</td>
</tr>
<tr>
<td></td>
<td>541.877</td>
<td>3d3</td>
<td>b 2D</td>
<td>5/2</td>
<td>3d2.(3F).4p</td>
<td>z 2F*</td>
<td>5/2</td>
<td>1.58</td>
<td>3.77E+05</td>
<td>1.66E-03</td>
</tr>
<tr>
<td>Cr II</td>
<td>455.864</td>
<td>3d5</td>
<td>b 4F</td>
<td>9/2</td>
<td>3d4.(5D).4p</td>
<td>z 4D*</td>
<td>7/2</td>
<td>4.07</td>
<td>8.80E+06</td>
<td>2.20E-02</td>
</tr>
<tr>
<td></td>
<td>484.825</td>
<td>3d4.(a 3F).4s</td>
<td>a 4F</td>
<td>7/2</td>
<td>3d4.(5D).4p</td>
<td>z 4F*</td>
<td>7/2</td>
<td>3.86</td>
<td>2.60E+06</td>
<td>9.20E-03</td>
</tr>
<tr>
<td></td>
<td>487.649</td>
<td>3d4.(a 3F).4s</td>
<td>a 7F</td>
<td>7/2</td>
<td>3d4.(5D).4p</td>
<td>z 4F*</td>
<td>5/2</td>
<td>3.86</td>
<td>1.60E+06</td>
<td>4.30E-03</td>
</tr>
<tr>
<td>Fe I</td>
<td>417.212</td>
<td>3d7.(2D2).4s</td>
<td>a 3D</td>
<td>3</td>
<td>3d7.(2F).4p</td>
<td>w 3P*</td>
<td>2</td>
<td>3.25</td>
<td>9.80E+06</td>
<td>1.83E-02</td>
</tr>
<tr>
<td></td>
<td>503.078</td>
<td>3d7.(2H).4s</td>
<td>b 3H</td>
<td>6</td>
<td>3d6.(3H).4s.(3P*) z 3I*</td>
<td>7</td>
<td>3.24</td>
<td>2.60E+04</td>
<td>1.14E-04</td>
<td>−2.83</td>
</tr>
<tr>
<td></td>
<td>525.496</td>
<td>3d6.4s2</td>
<td>a 5D</td>
<td>1</td>
<td>3d5.(5D).4s.(3P*) z 7D*</td>
<td>2</td>
<td>0.11</td>
<td>8.31E+02</td>
<td>5.74E-06</td>
<td>−4.76</td>
</tr>
<tr>
<td></td>
<td>528.442</td>
<td>3d6.4s2</td>
<td>a 11</td>
<td>6</td>
<td>3d6.(3G).4s.(3P*) y 5H*</td>
<td>5</td>
<td>3.63</td>
<td>8.29E+04</td>
<td>2.94E-04</td>
<td>−2.42</td>
</tr>
<tr>
<td>Fe II</td>
<td>441.682</td>
<td>3d6.(3P2).4s</td>
<td>b 4P</td>
<td>1/2</td>
<td>3d6.(5D).4p</td>
<td>z 4D*</td>
<td>3/2</td>
<td>2.78</td>
<td>2.10E+05</td>
<td>1.30E-03</td>
</tr>
<tr>
<td></td>
<td>449.140</td>
<td>3d6.(3F2).4s</td>
<td>b 4F</td>
<td>3/2</td>
<td>3d6.(5D).4p</td>
<td>z 4F*</td>
<td>3/2</td>
<td>2.86</td>
<td>1.90E+05</td>
<td>5.70E-04</td>
</tr>
<tr>
<td></td>
<td>454.152</td>
<td>3d6.(3F2).4s</td>
<td>b 4F</td>
<td>3/2</td>
<td>3d6.(5D).4p</td>
<td>z 4D*</td>
<td>3/2</td>
<td>2.86</td>
<td>9.00E+04</td>
<td>2.70E-04</td>
</tr>
<tr>
<td></td>
<td>457.633</td>
<td>3d6.(3F2).4s</td>
<td>b 4F</td>
<td>5/2</td>
<td>3d6.(5D).4p</td>
<td>z 4D*</td>
<td>5/2</td>
<td>2.84</td>
<td>6.40E+04</td>
<td>2.00E-04</td>
</tr>
<tr>
<td></td>
<td>462.051</td>
<td>3d6.(3F2).4s</td>
<td>b 4F</td>
<td>7/2</td>
<td>3d6.(5D).4p</td>
<td>z 4D*</td>
<td>7/2</td>
<td>2.83</td>
<td>2.50E+04</td>
<td>8.10E-05</td>
</tr>
</tbody>
</table>

Continued on Next Page...
Table 5.6 – Continued

<table>
<thead>
<tr>
<th>Spec (nm)</th>
<th>Lower level</th>
<th>Upper level</th>
<th>$J_i$</th>
<th>$J_k$</th>
<th>$E_i$ (eV)</th>
<th>$E_k$ (eV)</th>
<th>$A_{ki}$ ($s^{-1}$)</th>
<th>$f_{ik}$</th>
<th>log(gf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>523.462</td>
<td>3d6.(3G).4s a 4G 7/2 3d6.(5D).4p</td>
<td>z 4F* 5/2 3.22 5.59 2.50E+05 7.60E-04</td>
<td>-2.21</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>553.484</td>
<td>3d6.(3H).4s b 2H 11/2 3d6.(5D).4p</td>
<td>z 4F* 9/2 3.24 5.48 3.00E+04 1.10E-04</td>
<td>-2.90</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>623.838</td>
<td>3d6.(3D).4s b 4D 3/2 3d6.(5D).4p</td>
<td>z 4P* 3/2 3.89 5.88 8.00E+04 4.40E-04</td>
<td>-2.80</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>624.756</td>
<td>3d6.(3D).4s b 4D 5/2 3d6.(5D).4p</td>
<td>z 4P* 3/2 3.89 5.88 1.60E+05 6.00E-04</td>
<td>-2.40</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>641.693</td>
<td>3d6.(3D).4s b 4D 5/2 3d6.(5D).4p</td>
<td>z 4P* 5/2 3.89 5.82 4.00E+04 2.20E-04</td>
<td>-2.90</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>643.268</td>
<td>3d5.4s2 a 6S 5/2 3d6.(5D).4p</td>
<td>z 6D* 5/2 2.89 4.82 8.50E+03 5.30E-05</td>
<td>-3.50</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>651.608</td>
<td>3d5.4s2 a 6S 5/2 3d6.(5D).4p</td>
<td>z 6D* 7/2 2.89 4.79 8.30E+03 7.10E-05</td>
<td>-3.37</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sr II</td>
<td>407.771 4p6.5s 2S 1/2 4p6.5p</td>
<td>2P* 3/2 0.00 3.04 1.41E+08 7.03E-01</td>
<td>0.148</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>421.552</td>
<td>4p6.5s 2S 1/2 4p6.5p</td>
<td>2P* 1/2 0.00 2.94 1.26E+08 3.36E-01</td>
<td>-0.17</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Note:** This table contains NIST data for the atomic transitions that contribute to significant ($\%p > 4\sigma$) polarization. See additional data for lines that are also polarized out-of-eclipse in Chapter 4 (Paper 1). The spectrum, laboratory wavelength, and the lower and upper configuration, terms and $J$ value of the transition are given as well as the energies, Einstein coefficient for spontaneous emission, the oscillator strength and log(gf). An asterisk indicates odd parity.
Figure 5.1: Fe II 658.370 nm weak line transient feature for two observations 2009–09–26 and 2009–12–02. The feature moved from red–shifted to blue–shifted of the line rest velocity in both out–of–eclipse and eclipse spectra. The data are unbinned ESPaDOnS intensity profiles that have been corrected for F0 star motion. Two échelle orders are present in each spectrum.
Figure 5.2: \(\varepsilon\) Aurigae light curve for the period between 1\textsuperscript{st} and 2\textsuperscript{nd} contact (bottom). The \(V\) band magnitude data were sigma clipped for S/N > 500 and fit with a 2\textsuperscript{nd} order polynomial (blue curve) and a 3\textsuperscript{rd} order polynomial (red curve) in order to remove the eclipse effects (see text). The residuals of the 3\textsuperscript{rd} order polynomial fit (top) still show the imprint of the underlying F star variability (\(\sim\)0.1 mag, \(\sim\)67 day period). Average magnitudes for the epoch–binned ESPaDOnS observations are indicated on the light curve (red circle). The uncertainties are within the symbol size. Note the ESPaDOnS observations do not appear to fall during periods when the star is trending brighter (negative residual) or dimmer (positive residual) than the model fit.
Figure 5.3: Ti $\text{II}$ 450.127 nm and Fe $\text{II}$ 501.844 nm intensity (top) and polarization (bottom) spectra for 2009–09–04 (RJD 55086) about 2 weeks after 1st contact. The dashed line is a pre–eclipse (epoch–binned 2008–12–07 through 2008–12–10) line profile for comparison with the observation (solid line). The two absorption lines are broadened in this epoch and have an additional red–shifted ($+15 \text{ km s}^{-1}$) absorption component. The linear polarization ($%p$) may be bi–lobed (see text). The polarization extends far into the blue wing in the deeper line. Polarization in the far blue wing may probe scattering regions close to the disk center with high negative velocities ($-100 \text{ km s}^{-1}$).
Figure 5.4: Fe ii (531.660 nm) observation 2010–10–16 made just after mid-eclipse (2010–07–22 ± 30 days) exhibits disk rotation signatures. Left: additional blue-shifted absorption is present in the line (top). Percent linear polarization (%p) appears bi–lobed (bottom). Four sigma or greater peaks (blue diamonds) and three sigma peaks (green asterisk) are indicated. Right: Stokes Q exhibits two peaks across the line (top) and Stokes U is antisymmetric around zero (bottom). Stokes Q, Stokes U (and resultant %p) are binned data (bin size 0.008 nm), that have been adjusted for stellar motion and rotated into the stellar reference frame. Zero velocity centered on the line rest wavelength.
Figure 5.5: Fe II (531.660 nm) position angles exhibit characteristic signature of rotating gas in this 2010–10–16 observation made just after mid-eclipse. Data are binned (bin size 0.008 nm), have been adjusted for stellar motion and have been rotated into the stellar frame. Blue wing (blue asterisk), red wing (red asterisk) and line center (± 25 km s⁻¹; green asterisk) position angles are indicated. Angles were wrapped so that high PA (>150°) plotted as low angles. Note that the discontinuous angles would plot increasingly negative, consistent with models (see text).
Figure 5.6: Si ii 634.710 nm absorption line equivalent width (top) and polarized flux EW (bottom). Polarized flux are epoch–binned to reduce noise. Mid–eclipse (dashed line) and 1st, 2nd, 3rd & 4th contacts indicated (green lines). The high energy transition ($E_{\text{ll}} > 3$ eV) is classified as a line with no/low additional disk absorption during eclipse (Strassmeier et al., 2014). Small fluctuations in EW and large fluctuations in polarized flux EW are observed out–of–eclipse (OOE). The OOE polarization is confined to the line core ($0 \pm 20$ km s$^{-1}$). The line does not show a large increase in EW during eclipse, but there is a small increase and then a steady decrease after 1st contact. Polarized flux EW is greatest before and after mid–eclipse; the polarization observed in these epochs has a disk rotation signature (see text). The polarized flux drops to low levels at mid–eclipse. Polarized flux is zero by 4th contact.
Figure 5.7: Si II 634.710 nm line profile (top) and polarization (bottom) observed out–of–eclipse on 2009–02–13 (left) and 4 months prior to mid–eclipse 2010–03–08 (right). The observed line profile (solid line) is plotted with an out–of–eclipse profile for comparison (dashed). Significant polarization (> 4σ) is indicated (blue diamonds). Polarization is confined to the line core (0 ± 20 km s⁻¹) out–of–eclipse even though the line is evidently variable. A red–shifted polarization appears in the eclipse observation when the line is also red–shifted.
Figure 5.8: Si II 634.710 nm line profile (top) and polarization (bottom) observed during eclipse on 2010–10–16 (left) and 2010–11–15 (right). The observed line profile (solid line) is plotted with an out-of-eclipse profile for comparison (dashed). Significant polarization ($>4\sigma$) is indicated (blue diamonds). The line is initially blue–shifted $-20\text{ km s}^{-1}$, the $\%p$ is bi–lobed and the $\%p$ amplitude is lower. About one month later the line is less blue–shifted, now at $-10\text{ km s}^{-1}$, and $\%p$ is no longer bi–lobed. The EW of the line in these observations is less than the average out–of–eclipse EW. Note the large change to $\%p$ on a short timescale ($\sim 1$ month).
Figure 5.9: Si II 634.710 nm observation 2010–10–16 position angles (PA) (top) and QU–plot (bottom). Line core data (green) are defined as $0 \pm 20 \text{ km s}^{-1}$, blue wing data (blue) are $-20 \text{ km s}^{-1}$ to $-100 \text{ km s}^{-1}$ and red wing data (red) are $+20 \text{ km s}^{-1}$ to $+100 \text{ km s}^{-1}$. The position angles across the line are imprinted with the signature of disk rotation (see text). The polarization data form a linear extension when plotted in %q and %u because there are no contributions from %q to the polarization observed in this epoch (Fig 5.10).
Figure 5.10: Si $\textit{ii}$ 634.710 nm (left) and Mg $\textit{ii}$ 448.113 nm (right) line profile, $%q$ and $%u$ for the 2010–10–16 observation near mid–eclipse. The line profiles are nearly symmetric (top). Si $\textit{ii}$ 634.710 nm has no polarization signal in $%q$ (middle), while Mg $\textit{ii}$ 448.113 nm has the opposite sign in the red wing compared to the line core. $%u$ (bottom) displays the characteristic reversal associated with rotation (see text). Both lines are considered F0 star only lines with low/no disk absorption during eclipse, however scattering is clearly occurring at these wavelengths.
Figure 5.11: Mg ii 448.113 nm absorption line equivalent width (top) and polarized flux EW (bottom). Polarized flux data are epoch–binned to reduce noise. Symbols as in Fig. 5.6. The line has no disk absorption during eclipse (Strassmeier et al., 2014); compare to Si ii 634.710 nm (Fig 5.6). The line is not polarized out–of–eclipse. There is no large increase in EW during eclipse, but there is a small increase and then a steady decrease in EW after 1st contact. Polarized flux EW is greatest after mid–eclipse; the polarization observed in these epochs has a disk rotation signature (see text). The polarized flux drops to low levels at mid–eclipse. Polarized flux is zero by 4th contact.
Figure 5.12: Mg II 448.113 nm line profile (top) and polarization (bottom) observed during eclipse on 2010–10–16 (left) and 2010–11–15 (right). The observed line profile (solid line) is plotted with an out–of-eclipse profile for comparison (dashed). Significant polarization ($> 4\sigma$) is indicated (blue diamonds). The line is slightly blue–shifted in the observation about 3 months after mid–eclipse (2010–10–16) and then is centered on the rest velocity but deeper in the later observation (2010–11–15). Note $%p$ is bi–lobed in both observations. Also note the large change to $%p$ on a short timescale ($\sim$ 1 month).
Figure 5.13: Mg ii 448.113 nm observation 2010–10–16 position angles (PA) (top) and QU–plot (bottom). Line core data (green) are defined as 0 ± 20 km s\(^{-1}\), blue wing data (blue) are −20 km s\(^{-1}\) to −100 km s\(^{-1}\) and red wing data (red) are 20 km s\(^{-1}\) to 100 km s\(^{-1}\). The position angles across the line are imprinted with the signature of disk rotation (see text). The polarization data form a loop when plotted in %q and %u because there are contributions to polarization from both Stokes parameters (Fig 5.10).
Figure 5.14: Fe \( \text{II} \) 473.144 nm absorption line equivalent width (top) and polarized flux EW (bottom). Polarized flux data are epoch–binned to reduce noise. Symbols as in Fig. 5.6. The line was characterized as having no/low disk absorption during eclipse (Strassmeier et al., 2014). The line exhibits small rise in EW throughout eclipse and large fluctuations in polarized flux EW. There appears to be no decrease in EW after 1\textsuperscript{st} contact. The polarization out–of–eclipse is confined to the line core (0 ± 20 km s\(^{-1}\)). Note the large increase in polarized flux after mid–eclipse, similar to Si \( \text{II} \) 634.710 nm (Fig. 5.6). Polarized flux is very low by 4\textsuperscript{th} contact.
Figure 5.15: Ca i 422.673 nm absorption line equivalent width (top) and polarized flux EW (bottom). Polarized flux data are epoch–binned to reduce noise. Symbols as in Fig. 5.6. This medium strength line arises from a ground state transition. The line has obvious contributions to EW from disk absorption, but the EW is variable. Polarized flux presents similar behavior, but greater amplitude, than many other lines presented here. Compare this line to Fe ii 531.661 nm (Fig. 5.17), for example.
Figure 5.16: Fe ii 527.600 nm absorption line equivalent width (top) and polarized flux EW (bottom). Polarized flux data are epoch–binned to reduce noise. Symbols as in Fig. 5.6. The strong line exhibits obvious disk contributions to EW during eclipse and large changes to polarized flux EW. The EW does not decrease noticeably after 1st contact before rising again as the eclipse progresses. Note the increase in polarized flux after mid–eclipse, similar to others presented here. Polarized flux is zero by 4th contact, although the line has not yet returned to its pre–eclipse EW. Compare this line to Fe ii 531.661 nm from the same multiplet (Fig. 5.17), plotted on the same scale. The sister line shows a decrease in EW after 1st contact.
Figure 5.17: Fe II 531.661 nm absorption line equivalent width (top) and polarized flux EW (bottom). Polarized flux data are epoch–binned to reduce noise. Symbols as in Fig. 5.6. The strong line exhibits obvious disk contributions to EW during eclipse and large changes to polarized flux EW. The EW decreases after 1st contact before rising again as the eclipse progresses. Note the increase in polarized flux after mid–eclipse, similar to others presented here. Polarized flux is zero by 4th contact, although the line has not yet returned to its pre–eclipse EW. Compare this line to Fe II 527.600 nm from the same multiplet (Fig. 5.16), plotted on the same scale. The Fe II 527.600 nm line is slightly stronger in EW, but not in polarized flux.
Figure 5.18: H\textsc{i} 656.280 nm (H\textalpha) absorption line equivalent width (top) and polarized flux EW (bottom). Polarized flux data are epoch–binned to reduce noise. Symbols as in Fig. 5.6. Large blue–shifted absorption contributes to the EW of the line by mid–eclipse until 3\textsuperscript{rd} contact. Polarized flux shows a large increase in scattered light after 1\textsuperscript{st} contact until 3\textsuperscript{rd} contact. Note the mid–eclipse EW remains high in this line.
Figure 5.19: H\textsc{i} $656.280$ nm (H\textalpha) line profile, Stokes Q ($%q$) and Stokes U ($%u$) for a late–eclipse epoch 2010–11–15. The data have NOT been adjusted for F0 star motion (RV $-1.7$ km s$^{-1}$). The Stokes parameters probe four distinct velocity regimes: (1) red–shifted absorption $(+15$ km s$^{-1}$) at $(-%q,-%u)$, (2) low negative velocity $(-15$ km s$^{-1}$) at $(-%q,+%u)$, (3) medium negative velocity $(-50$ km s$^{-1}$) at $(+%q, 0.0)$ and (4) high negative velocity $(-130$ km s$^{-1}$) at $(+%q,-%u)$. 

201
Figure 5.20: H\textsc{i} 656.280 nm (H\textalpha) position angle (PA) plot for a late–eclipse epoch 2010–11–15. The data have NOT been adjusted for F0 star motion (RV $-1.7$ km s$^{-1}$). The Stokes parameters probe four distinct velocity regimes: (1) red–shifted absorption (+15 km s$^{-1}$) at ($-\%q,-\%u$), (2) low negative velocity ($-15$ km s$^{-1}$) at ($-\%q,+\%u$), (3) medium negative velocity ($-50$ km s$^{-1}$) at ($+\%q, 0.0$) and (4) high negative velocity ($-130$ km s$^{-1}$) at ($+\%q,-\%u$). Compare this plot with Figure 5.19.
Figure 5.21: H I 656.280 nm (Hα) absorption line (top), Stokes Q (middle), and Stokes U (bottom) for a pre–eclipse epoch 2008–10–18 (left) and a post–eclipse epoch 2012–12–09 (right). Stokes Q (%q) is consistently negative in the line core throughout eclipse. Stokes U (%u) is negative before eclipse, is complex during mid–eclipse epochs and then becomes positive by 2011–08–17 (RJD 5791; phase 0.129) at 4th contact. Stokes U remains positive in subsequent observations. The line has returned to its pre–eclipse profile by our last observation, 2012–12–09, about 1.5 years after 4th contact. The two observations presented here occurred at nearly opposite epochs from mid–eclipse. Note the RV correction is nearly the same, but negative in the later observation.
Figure 5.22: H i 656.280 nm (Hα) absorption line (top) and polarization spectrum (bottom) for a post–eclipse epoch 2012–12–09, about 1.5 years after 4th contact. The line has returned to its pre–eclipse profile but with smaller emission wings. An out–of–eclipse (epoch–binned 2008–12–07 through 2008–12–10) line profile (dashed line) is plotted for comparison. Linear polarization is present and is associated with the line core. Stokes $Q$ and $U$ for this polarization profile are shown in Figure 5.21.
Figure 5.23: H I 486.135 nm (Hβ) absorption line equivalent width (top) and polarized flux EW (bottom). Polarized flux data are epoch–binned to reduce noise. Symbols as in Fig. 5.6. Large blue–shifted absorption contributes to the EW of the line by mid–eclipse until 3rd contact. Polarized flux generally increases after 1st contact until 3rd contact. Compare this line with Hα (Fig. 5.21). The scattering behavior is consistent between the two lines, but the scattered flux is much lower in Hβ.
Figure 5.24: H I 486.135 nm (Hβ) intensity (top) and polarization (bottom) spectra for 2009–09–04 (RJD 55086) about 2 weeks after 1st contact. The dashed line is a pre–eclipse line profile for comparison with the observation (solid line). The absorption line is broadened and has an additional red–shifted (+15 km s$^{-1}$) absorption component. The equivalent width is $\sim$10% greater in this observation compared with the pre–eclipse observation (Table 5.2). The linear polarization (%p) peaks at the line core and extends far into the blue wing. Polarization in the far blue wing may probe scattering regions close to the disk center with high negative velocities ($-100$ km s$^{-1}$). Compare to Figure 5.2.
Figure 5.25: Ca\textsc{ii} 866.214 nm absorption line equivalent width (top) and polarized flux EW (bottom). Polarized flux data are epoch–binned to reduce noise. Symbols as in Fig. 5.6. This is a low energy ($E_\parallel < 3$ eV) but high eccentricity ($e > 0.3$) line (Strassmeier et al., 2014). The line is unusual because the peak polarization occurs before 2\textsuperscript{nd} contact rather than near 3\textsuperscript{rd} contact. The EW remains high after 4\textsuperscript{th} contact probably because of gas trailing behind the dusty opaque disk Griffin and Stencel (2013).
Figure 5.26: Ca II 866.214 nm absorption line profile (top) and polarization spectrum (bottom) for 2009–12–02 (RJD 55174) about 3 months after 1st contact and 2.5 months before 2nd contact. The dashed line is a pre–eclipse line profile for comparison with the observation (solid line). The absorption line is broadened and has an additional red–shifted (+20 km s$^{-1}$) absorption component. The linear polarization ($\%p$) extends far into the blue wing. Note that the equivalent width of the line in this epoch is about 5% greater than the EW in the epoch of comparison (RJD 54811). Compare to H$\beta$ (Fig. 5.24).
Figure 5.27: Broadband and line polarization peaks by orbital phase. The change in V band continuum polarization from minimum for the 1982–1984 eclipse (blue diamonds) and 2009–2011 eclipse (green triangles) plotted by phase using the ephemeris of Stefanik et al. (2010). The change to polarized flux EW for Fe II is plotted for comparison (red squares). The data have been scaled so the largest values are equal. The data are differenced from the minimum (Δ %p or Δ pol flux EW) and represent the change to the measured value. Units are Δ [%] or Δ [mA]. The line polarization peak occurs prior to the continuum polarization peak near 3rd contact. The line data are shifted by phase to align the steep decrease at phase 0.11. The phase shift corresponds to 90 days (purple diamonds). An Mg II line is scaled and shifted by 90 days for comparison (black diamond). The underlying F0 star variability (∼100 days) is apparent in the Δ %p data.
Chapter 6

HPOL out–of–eclipse observations of $\varepsilon$ Aurigae

6.1 Summary

We tested the hypothesis that the F0 star in the $\varepsilon$ Aurigae system shows intrinsic broadband polarization and that the percent linear polarization ($%p$) is related to the brightness of the variable F0 star observed out–of–eclipse. We tested whether dust grains in the disk are small ($\ll 10\mu m$) or large ($>10\mu m$) by revealing the position angle of intrinsic linear polarization. We characterized the contribution of interstellar polarization using archived data from the HPOL polarimeter and published broadband filter data from the literature. We subtracted the interstellar component from previously published broadband out–of–eclipse and in–eclipse observations to characterize the intrinsic polarization of the system. We find that intrinsic continuum observed out–of–eclipse (OOE) is sometimes wavelength–dependent. Changes to $%p$ are not correlated with changes in magnitude. We uncovered the underlying intrinsic polarization in published eclipse data to find an intrinsic linear polarization position angle of $\sim90^\circ$ in the stellar/disk reference frame during mid–eclipse phases. Polarization during eclipse primarily arises from forward–scattering at large dust grains or from multiple scattering from optically–thick dusty material. Optically thin scattering from small grains would yield position angles closer to $0^\circ$ in the stellar/disk reference frame. The presence of large dust grains suggests that the disk is an evolved debris disk rather than a young proto-planetary disk and that the F0 star in the system is also an evolved star.
6.2 Introduction

The $\varepsilon$ Aurigae system is a known irregularly variable eclipsing system with typical non-periodic $V$ band brightness variations of $\sim 0.1$ mag and an eclipse variation of $0.8$ mag. There is a close linear correlation between brightness and color: the star is bluest (hottest) when brightest (Gyldenkerne, 1970; Carroll et al., 1991). Epsilon Aurigae was classified as an $\alpha$ Cygni type variable star using an automated classification of the Hipparcos periodic variable stars into 26 types using a random forest method (Dubath et al., 2011). $\alpha$ Cygni variable stars are classified by the American Association of Variable Star Observers (AAVSO) as non-radially pulsating supergiants of Bep-Aep Ia spectral types\(^1\). A quasi-period of $\sim 67$ days may be present in both brightness and radial velocity (RV) variations (Chadima et al., 2011; Kloppenborg et al., 2012; Strassmeier et al., 2014).

Observers have predicted the presence of a large opaque disk in the system to account for the observed light–curve during eclipse (e.g. Kopal, 1954; Huang, 1965). Backman et al. (1984) detected an infrared excess using broadband filters ($\lambda = 1.25$–20 $\mu$m), which they attributed to an extended 500 K source. The presence of the disk was confirmed when the system was resolved interferometrically to show the eclipsing body moving in front of the F0 star. The body was found to be a geometrically thin, opaque disk seen nearly edge on whose perpendicular axis appears tilted at $\sim 27^\circ$ (east of north) to the line–of–sight (Kloppenborg et al., 2010). The opaque disk covers about one–half of the face of the F0 star during eclipse. However, even with these interferometric results, the nature and evolutionary status of the disk are still uncertain because the distance to the system is not well–defined.

\(^1\)AAVSO online at: http://www.aavso.org
A range of distances are proposed for the system, leading to a large range of mass ratios, defined as \( q = M_1/M_2 = M_{F*}/M_{B*} \). However, two mass solutions are often proposed: “high mass” and “low mass” which correspond to two representative mass ratios \( q = 0.75 \) and \( q = 1.25 \) and distances \( d(0.75) = 740 \) pc and \( d(1.25) = 952 \) pc (Pearson and Stencel, 2015). The high mass solution implies the system is less evolved with a supergiant primary star and a companion hidden in a proto–planetary disk. The low mass scenario implies a post–Asymptotic Giant Branch (post–AGB) primary star and an evolved debris disk (Guinan, 2010). The secondary star is likely a spectral type B star (Hack, 1959; Hoard et al., 2010).

We adopt orbital elements given by Stefanik et al. (2010) in our analysis: phase 0.0 corresponds to periastron and mid–eclipse occurs at phase \( \sim 0.09 \) (JD 2,455,413.8 \( \pm \) 4.8, 2010 August 5). In this reckoning, the photometric eclipse begins near phase 0.056 and ends near phase 0.130, apastron is at phase 0.5 and secondary eclipse (never observed at visible wavelengths) occurs near phase \( \sim 0.6 \). The mass function is given by \( f(M_\odot) = (M_2 \sin i)^3/(M_1 + M_2)^2 = 2.51 \pm 0.12 \) (Stefanik et al., 2010).

Relevant distances are given in Table 6.1 for two mass ratios. The distance between the F0 star and the disk more than doubles from 9 AU to 22 AU \( (q = 0.75) \) or from 13 AU to 28 AU \( (q = 1.25) \) between periastron and apastron (orbital phases 0.0 to 0.5). The distance between the F0 star and the disk increases from \( \sim 18 \) AU to 22 AU \( (q = 0.75) \) or from \( \sim 23 \) AU to 28 AU \( (q=1.25) \) between phases 0.35 and 0.50, an interval similar to the first six out–of–eclipse HPOL observations. This change in distance corresponds to about 20% of the maximum separation between the F0 star and the disk.
Intrinsic polarization in the system was first discovered by Coyne (1972). Polarization observations of ε Aurigae over four years after 1967 showed a change in the observed broadband polarization. A continuous change in polarization was observed beginning just before orbital phase 0.49 continuing to phase 0.63 (calculated from periastron) using the ephemeris from Stefanik et al. (2010). Coyne noted that the degree of interstellar polarization in the vicinity of ε Aurigae was not known, but that as much as one–quarter of the observed polarization could be intrinsic. Henson (1989) estimated that the intrinsic polarization varied by a few tenths of a percent around a persistent ∼2% interstellar polarization.

Wolff et al. (1996) observed the epsilon Aurigae system six times in the 1990s using the HPOL medium resolution spectropolarimeter at the University of Wisconsin’s Pine Bluff Observatory. These authors published data from ε Aurigae and 8 other objects in order to characterize the interstellar polarization curve along moderately–reddened lines of sight. They averaged the HPOL data to reduce the contribution of any low level of polarimetric variability present in each observed object in the study. We re–analyzed the HPOL data because we were specifically interested in the low level of variability seen in the ε Aurigae polarization. We also obtained new observations of ε Aurigae with the refurbished HPOL at Ritter Observatory in 2012 and 2013 (Davidson et al., 2014). We included broadband polarization observations taken during the recent 2009–2011 eclipse (Cole, 2012), and during and after the prior 1982–1984 eclipse (Kemp et al., 1986; Henson, 1989).

The paper is organized as follows: observations and reductions are described in Section 6.3; the results and analysis of out–of–eclipse data are given in Section 6.4 and for eclipse data in Section 6.5; discussion and conclusions are presented
in Section 6.6 and Section 6.7. Finally, a discussion of our model for interstellar polarization along the $\varepsilon$ Aurigae line–of–sight may be found in the Appendix.

6.3 Observations and Reductions

Wolff et al. (1996) obtained visible–wavelength medium–resolution spectra and polarized spectra for $\varepsilon$ Aurigae using the HPOL spectropolarimeter at the University of Wisconsin’s 0.9 m telescope at Pine Bluff Observatory (PBO) near Madison, Wisconsin. They obtained 5 observations in 1990–1992 using a Reticon dual–channel photo–diode array detector with 25 Å resolution. PBO staff conducted one unpublished observation in 1996 using the newer CCD detector (resolution 7.5 Å below 6000 Å and 10 Å above; Nordsieck and Harris, 1996; Davidson et al., 2014).

HPOL spectra were convolved with artificial broadband filter functions as part of the pipeline reduction to create simulated $UX$, $B$, $V$, $R$, $I$ band observations. We obtained synthetic filter data for all the $\varepsilon$ Aurigae observations from the MAST archive\(^2\); the filter data are also available at the HPOL website\(^3\). We also observed the system three times in 2012 and 2013 with the refurbished HPOL spectropolarimeter at the University of Toledo’s Ritter Observatory in Toledo, OH (Davidson et al., 2014). These observations used the same CCD detector as in 1996. All HPOL observations are tabulated in Table 6.2. Filter data are presented in Table 6.3.

We included previously–published broadband $B$, $V$, $R$ polarization data for the most recent (2009–2011) eclipse that extended for several months beyond 4$^{th}$ contact (Cole, 2012). We also included previously–published $U$, $B$, $V$ broadband filter observations from the prior (1982–1984) eclipse that extended for approximately

\(^2\)MAST online at: https://archive.stsci.edu

\(^3\)HPOL online at: http://www.sal.wisc.edu/HPOL/
4 years after eclipse (1982 August 23 to 1988 April 25; Henson, 1989). Finally, we included broadband $U$, $B$, $V$, $R$ polarization data, catalogued for $\varepsilon$ Aurigae from observations at the Flower and Cook Observatory (FCO), University of Pennsylvania for comparison (Elias et al., 2008). The system was observed in $U$, $B$, $V$, $R$ bands on 1975 Oct 04 and in $B$ band on 1975 Jan 06 (Table 6.4). No published photometric observations correspond to the FCO polarization observations.

We obtained $U$, $B$, $V$ photometric observations from the AAVSO around the date of each HPOL polarization observation. We calculated the mean magnitude for $\varepsilon$ Aurigae using a rolling 7-day window centered on each HPOL observation date. We estimated uncertainty in the magnitude using the standard deviation of the brightness observations. Average magnitudes may be found in Table 6.5.

### 6.3.1 Spectra

We binned HPOL spectra by uncertainties in order to facilitate comparison between Reticon and CCD observations. We binned wavelengths greater than 6000 Å to constant internal error of 0.02% and binned wavelengths less than or equal to 6000 Å to constant internal error of 0.03%, where the errors are the uncertainties in Stokes parameters described by Wolff et al. (1996). We adopted the larger of either the systematic (instrumental) or intrinsic uncertainty for each broadband filter observation (cf. the section on uncertainties) (Davidson et al., 2014).

We fit the full HPOL spectrum from each observation using a Serkowski law (Serkowski et al., 1975), fitting $%q$ and $%u$ data simultaneously. We first fit the data without a position angle rotation and then compared that fit to one that allowed for position angle rotation, described below (see Table 6.6). Free parameters of the first fit were the maximum Stokes vectors $q_{max}$ and $u_{max}$; the wavelength
corresponding to the maximum polarization, $\lambda_{\text{max}}$ [\(\mu\text{m}\)]; and $K$, the parameter that describes the width of the curve. We used \textit{mpfit}\textsuperscript{4} to apply a least squares fit to the data. We also fit the full HPOL spectrum from each observation using a variation of the method described by Wolff et al. (1996) allowing for a position angle rotation, fitting $%q$ and $%u$ data simultaneously. Free parameters of the fitting were the maximum Stokes vectors $q_{\text{max}}$ and $u_{\text{max}}$; the wavelength corresponding to the maximum polarization, $\lambda_{\text{max}}$ [\(\mu\text{m}\)]; the starting angle for the fit, $\theta_0$; and $d\theta/dx$, where $x = \lambda$ and $d\theta/dx$ is the rotation about position angle $\theta$. We fit parameter $K$ using the relation derived by Whittet et al. (1992). Results of fitting are tabulated in Table 6.6.

We adopted a model for interstellar polarization (see Appendix) and removed its polarization contribution from the binned data using Stokes $q$ and $u$. We calculated the intrinsic linear polarization and position angle using the ‘intrinsic’ Stokes $q$ and $u$ and the method described by Bagnulo et al. (2009). We bias–corrected the intrinsic $%p$ and propagated uncertainties in $%p$ using Rician statistics (Clarke and Stewart, 1986). Finally, we rotated the intrinsic data by 27° using a rotation matrix (e.g. Bagnulo et al., 2009) to align instrument north with the presumed rotation axis of the system as described by Kloppenborg et al. (2010).

6.3.2 Broadband filter data

Artificial filter data are plotted by orbital phase in Figures 6.1 and 6.2. We also plotted the unrotated data from each filter in a QU–plot and noted a similar, apparently linear, trend (Fig. 6.3). The linear trend suggests a persistent preferred geometry for scattering in the system, likely related to the angle on the sky noted in interferometric observations. The eclipse model derived from interferometric $H$–band observations implied a northwest motion on the sky along a line with a position

\textsuperscript{4}Markwardt IDL Library online at: https://www.physics.wisc.edu/~craigm/idl/idl.html
angle of 296.82 ± 6.85 degrees at an inclination of $i = 84.30 \pm 0.15$ degrees (Kloppenborg et al., 2010). We assume the rotation axis of the system is oriented orthogonal to the eclipse plane which is viewed nearly edge–on. We fit a line to the artificial filter data using fitexy$^5$, which allows for uncertainties in both $x$ ($\%q$) and $y$ ($\%u$) data. Our results agree with the interferometric eclipse model within the uncertainties. Results of linear fitting to broadband filter data may be found in Table 6.7.

### 6.3.3 Polarized flux

We converted calibrated average magnitudes to flux densities in the HPOL units of flux (erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$) using the formulation by Bessell et al. (1998). We calculated polarized flux by multiplying the observed broadband polarization by the calibrated flux. The change in polarization, total flux and polarized flux relative to one observation are plotted in Figure 6.4.

### 6.3.4 Uncertainties

Uncertainties in archived HPOL broadband filter data are derived from photon statistics. In general, systematic uncertainties have been found to be greater than the archived percent errors. The medium mode systematic errors, or root–mean–squared (RMS) errors, have been well–characterized for $U$, $B$, $V$, $R$, $I$ observations dated after 1995 (Davidson et al., 2014). Prior to 1995, the uncertainties were estimated at 0.02%. We adopted either the tabled uncertainty (from the FITS file headers), or the systematic uncertainty (Table 6.8), whichever was greater, for our analysis, except in the linear least–squares fits to broadband data. We found that the smaller uncertainties associated with the CCD data greatly skewed the fits. We

adopted equal uncertainties of 0.02% for all observations when performing linear
least–squares fits to HPOL broadband filter data.

We adopted the formulation given by Bagnulo et al. (2009) for the uncertainty
in position angle, $\theta$, where

$$\sigma_\theta = \frac{1}{2} \times \frac{\sigma_{%p}}{%p}$$

(6.1)

Here $\sigma_\theta$ is the uncertainty in position angle (in radians) and $\sigma_{%p}$ is the uncertainty
in the degree of polarization.

We calculated the position angle from linear least–squares fits to broadband
data, $y = A + Bx$, as given by Quirrenbach et al. (1997).

$$B = \tan(2\theta)$$

(6.2)

Here parameter $B$ is the slope of the fit. We found the uncertainty in position angle
from the uncertain in parameter $B$ of the fit as follows

$$\sigma_\theta = \frac{1}{2} \sigma_B \times \frac{180}{\pi}$$

(6.3)

### 6.3.5 Balmer jump

Any changes in the observed polarization over a small wavelength range can be
entirely attributed to changes in the intrinsic component because the interstellar
polarization is essentially constant over small wavelength spans (Serkowski et al.,
1975). Polarimetric changes across the Balmer jump have been exploited to charac-
terize the position angle of the *intrinsic* polarization and then deduce the position
angle of the *interstellar* contribution (e.g. Quirrenbach et al., 1997; Wood et al.,
1997). This technique is useful when the intrinsic polarization position angle is
well-defined (i.e. the underlying geometry promotes scattering at coherent angles). In this case, the position angle is independent of wavelength, although the degree of polarization is generally not wavelength-independent: the continuum polarization level below the Balmer jump is lower than at wavelengths longer than the jump because the polarized flux is reduced by the hydrogen bound-free opacity.

We employed two additional HPOL synthetic filters in our analysis of the Balmer jump. One filter covers a range of wavelengths above the Balmer jump (BJ+) from 3650 Å and one covers the range below the Balmer jump (BJ−) from 3200 to 3650 Å, this filter measures the near-UV polarization. We removed the Interstellar polarization contribution from the observations by differencing the filter data (using %q and %u); the resulting degree of polarization and position angle may be used to characterize scattering geometries in the system (Hoffman et al., 1998). We have:

\[
\text{BJ}^+ - \text{BJ}^- = \text{BJ index}
\]

(6.4)

Where the BJ+ filter contains polarization contributions from both interstellar and intrinsic polarization, the BJ− filter is largely interstellar polarization and the BJ index is largely intrinsic polarization. Balmer jump data are presented in Table 6.9 and are plotted by %q and %u in Figure 6.5. Position angles calculated from Balmer jump data are plotted in Figure 6.6.

### 6.3.6 Interstellar polarization

The intrinsic and interstellar components of the polarization add vectorially to produce the total observed polarization. Interstellar polarization may be considered constant over a small range of wavelengths because it changes only gradually with wavelength. Because polarization is a vector sum, it is possible that an increase in polarization may yield an observed decrease in observed %p depending upon the
position angles of the components. The interstellar polarization signature must be removed from the observations to better understand the geometry contributing to the intrinsic continuum polarization. Establishing a well-defined value for the interstellar polarization (ISP) for $\varepsilon$ Aurigae has been difficult (Henson, 1989). However, the very small variability in the observed polarization suggests that the ISP is likely the greatest contributor to the observed polarization.

The intrinsic polarization position angle can be determined in several ways: (1) from time variability of the polarization; (2) from the difference between the continuum and H$\alpha$ emission line polarization, when present; (3) from polarization changes across the Balmer jump; and (4) from polarization changes across filter indices ($U$, $B$, $V$) (e.g. Clarke and Stewart, 1986; Quirrenbach et al., 1997). Hydrogen emission was not resolved in the medium-resolution HPOL spectra, leaving (1) the time variability of the polarization, (2) the polarization change across the Balmer jump and (4) changes in filter data as the most useful diagnostics available for our analysis. We identified three possible cases for the interstellar contribution to linear polarization: Cases A, B and C (see Appendix).

### 6.3.7 Adopted model for interstellar polarization

We chose Case A as the most likely method for estimating the interstellar polarization because it seemed reasonable that the observed intrinsic position angles should not vary widely on short timescales (see discussion, Appendix). We adopted the HPOL observation (1992–10–12) with a measured $%q$ and $%u$ closest (with the smallest chi-squared residual value) to the values obtained for the reference star (HD 32446), and with the least degree of polarization ($< 2\%$) as our estimate for interstellar polarization along the line-of-sight.
We chose this observation (1992–10–12) in order to avoid under-estimating the degree of interstellar polarization and to minimize the variation in intrinsic polarization position angle. Any value between the adopted (%q, %u) point and the reference star value (along the line of increasing %q, less negative %u) resulted in a smaller interstellar %p and larger intrinsic %p (Case B). Points on the linear least-squares fit to the left of the adopted epoch resulted in larger interstellar %p, but the resulting intrinsic polarization position angles varied more widely (Case C).

6.4 Results and analysis: Out-of-eclipse

6.4.1 General polarization features

HPOL observations may help characterize the polarization variability observed in the ε Aurigae system in both broadband and medium-resolution spectra outside of eclipse. The early HPOL observations (taken in the 1990s) span periastron; the most recent observations were taken after the eclipse of 2009–2011 when trailing material was no longer observed spectroscopically.

HPOL flux spectra are consistent with F0 star spectra described by others and are not discussed here, other than to comment that the flux spectra span the Balmer jump in all our HPOL observations. Polarization spectra (%p) closely followed a Serkowski curve (see fits, Table 6.6); another indication that the observed polarization is largely interstellar. We used HPOL broadband filter data in our analysis because of the better signal-to-noise when those filters were applied to the HPOL spectra. We observe variable polarization in both polarization spectra and filter data, confirming observations by others that the system is intrinsically polarized out-of-eclipse. We employed two Balmer jump artificial filters to identify polarization changes across the Balmer jump.
6.4.2 Intrinsic polarization – spectra

We find several epochs with residual intrinsic polarization after subtracting the model for interstellar polarization from the observations (e.g. Fig. 6.7). In one epoch, 1990–12–02, the intrinsic polarization shows a significant wavelength dependence across all wavelengths from \( \sim 3700 \, \text{Å} \) to 7000 \( \text{Å} \), with a peak polarization in the blue at \( \sim 3900 \, \text{Å} \) (Fig. 6.8). The wavelength dependence observed in this epoch is independent of the adopted model for interstellar polarization. The observed polarization position angle is coherent across wavelengths at \( \sim 90^\circ \) (Fig. 6.9). Blue–peaked wavelength–dependent intrinsic polarization and coherent position angles are observed in almost all other spectra. We observe no intrinsic polarization in the spectrum dated 1990–11–12.

The intrinsic wavelength dependence is not an artifact of the interstellar polarization subtraction because the phenomenon may be observed in the native HPOL data. Fig. 6.1 clearly shows an inversion of B band and R band polarization measured at several epochs (compare phase 1.365 with phase 1.372, for example). This figure also shows that the variation of the observed linear polarization occurs on timescales as short as a few weeks. There appears to be no trend of \( \%p \) with phase in these observations and no large change in polarization near apastron (phase 0.5).

Brightness variability is evident in the archived AAVSO data (Table 6.5). However, a change in broadband polarization is not always associated with a change in overall brightness in the system. For example, the \( V \) band polarization is at 2.14\% \( \pm 0.001\% \) on 2012–10–22 (phase 2.17) when the system is magnitude 3.02 \( \pm 0^m01 \) in \( V \) band. Compare this behavior with the \( V \) band observation dated 1990–12–02 (phase 1.365) when polarization is 2.07\% \( \pm 0.001\% \) and when the system is brighter at magnitude 2.97 \( \pm 0^m01 \) (Table 6.5 and Fig. 6.4).
6.4.3 **Intrinsic polarization – broadband filters**

Better signal to noise in the the HPOL artificial filter data reveal wavelength-dependent polarization in many of the observed epochs. Intrinsic polarization in spectra and broadband filters are compared in Figure 6.10. Intrinsic %p and position angle for synthetic filters are plotted in Figures 6.11 and 6.12. We used the same data reduction strategy with archived Flower and Cook observatory UBVR observations of ε Aurigae and note similar wavelength-dependent polarization.

Position angles also vary with time in both broadband data (Fig. 6.2) and spectra. Broadband polarization position angles vary as much as 4° on the sky in the timeframes observed. We find epochs when PA is different in each filter and epochs when PA is coherent across all observed bands. The two observations (1990–11–12 and 1992–02–27) with the most coherent PA filter behavior also have the largest measured position angles. We believe these epochs represent periods of very low/no intrinsic polarization. Coherent position angles are expected for interstellar polarization when little PA rotation is present.

Intrinsic polarization and position angles are presented in Table 6.10; we used both Case A and Case C models to subtract interstellar polarization for comparison.

6.4.4 **Intrinsic polarization – Balmer jump**

The observed position angle changes substantially from the early-epoch HPOL Balmer jump observations (1990–1996) to the most recent observation (2012). A large change in position angle could indicate an orbital component to the linear polarization observed out-of-eclipse. The Balmer jump index measures largely intrinsic polarization at near-UV wavelengths. The unrotated position angle changes from the 4th quadrant on the QU-plane (PA 135° to 180°) to the 2nd quadrant (45°
to 90°) over the ~16 year timeframe. These angles correspond to a change from 3rd quadrant (90° to 135°) in early observations to 1st quadrant (0° to 45°) when the data are rotated into the stellar–disk frame of reference. The 2012 observation corresponds to an earlier orbital phase (0.17) than the observations from the 1990s, which straddle apastron (phases 0.36 – 0.55).

We observe no trend in polarization to suggest a gradual increase in continuum polarization leading up to apastron, but our coverage is sparse. We find a position angle rotation in the most recent Balmer index observation (2012–10–22) that could be related to orbital changes. Brown et al. (1978) modeled a binary system with a circumbinary distribution of material and demonstrated a position angle rotation through all 4 quadrants of the QU–plane during one full orbit. Griffin and Stencel (2013) proposed that circumbinary material in the ε Aurigae system could account for a very deep (nearly zero flux), blue-shifted (−25 km s^{-1}) absorption component of the Ca i (393.333 nm) K line observed in many Dominion Astronomical Observatory (DAO) spectra. Boehm et al. (1984) found the ultraviolet (UV) emission line O I λ 1304 Å to be practically independent of eclipse and of UV variability. They also found that the emission wings of the chromospheric lines of Mg II ~2800 Å, observable in International Ultraviolet Explorer IUE high-resolution spectra, were independent of eclipse and of UV variability. These authors suggested that an extended envelope surrounding the whole system could account for the observations. Further spectropolarimetric observations of ε Aurigae, especially across the Balmer jump, could help determine whether orbital changes contribute to changing polarization position angles.
6.5 Results and analysis: Eclipse

Epsilon Aurigae was not observed by HPOL during eclipse. The system was observed in broadband filters by Kemp et al. (1986); Henson (1989) during the prior eclipse (1984–1986) and by one of us (G.C.) during the most recent eclipse (2008–2011). Recent eclipse data were presented in Cole (2012). We removed the interstellar contribution from eclipse data to reveal characteristics of the intrinsic eclipse polarization for the first time in this paper. For the prior eclipse data (Henson, 1989), we adopted the author’s estimate for interstellar polarization, subtracted that amount from Stokes Q and Stokes U and then calculated intrinsic \( %p \). We applied the interstellar estimate from HPOL Case A to the data from Cole (2012). Intrinsic \( V \) band polarization and position angles are presented in Figures 6.13 and 6.14. Intrinsic \( B \) band data is presented in Figures 6.15 and 6.16.

6.5.1 General polarization features

Percent polarization nearly doubles during the 2009–2011 eclipse compared to post–eclipse observations in broadband filter bands \( U, B, V, R \). Polarization changes accompany the light curve changes in both eclipse cycles (1984–1986 and 2009–2011). The presence of disk material contributes to the increase in polarization we observe in the broadband filters. The increase in intrinsic polarization is not large, only a few additional tenths of a percent, perhaps because of the additional absorption imposed by the optically thick disk material.

6.5.2 Intrinsic polarization – broadband filters

A low level of variable intrinsic continuum polarization is present in out–of–eclipse broadband filter data (%p = 0.1–0.4, \( V \) band). The intrinsic polarization increases during eclipse (%p = 0.4 – 0.8, \( V \) band) with a large increase (>3\( \sigma \)) of
short duration near 3rd contact in B band and V band during the recent eclipse, and in U, B, and V bands during the prior eclipse. Intrinsic polarization (%p) for both eclipses is plotted by orbital phase in Figures 6.13 and 6.15. The amplitude of the intrinsic polarization (%p) is larger in B band than in V band or U band (not plotted). Kemp et al. (1986) found nearly color independent variation in (interstellar + intrinsic) Stokes Q and U in filter bands U, B, V during the prior eclipse. The largest amplitude was observed in Stokes Q in V band. However, the data are dominated by the interstellar polarization which peaks in V band. We observe the wavelength–dependent peak in %p in B band once the interstellar component is removed from the combined data. We also note that the polarization peak in %p near 3rd contact is also present in combined (interstellar + intrinsic) data and is independent of the choice of interstellar polarization model.

The position angle of intrinsic polarization varies around ~90° from mid–eclipse to 3rd contact in B band and V band during both eclipse cycles (Figs. 6.14 and 6.16) and in U band during the prior eclipse (not plotted). The position angle decreases after 3rd contact to 4th contact during the prior eclipse, but we do not observe this trend in our data during the most recent eclipse. The position angle of intrinsic polarization is much more variable out–of–eclipse.

The position angle of intrinsic polarization depends more strongly than intrinsic %p on the choice of ISP model. The ISP model Case C produced residual intrinsic position angles that varied from 90° to 135° in HPOL out–of–eclipse data (Fig. 6.12). The Case C model amounts to an offset by about 30° from the Case A model presented here. Regardless of the choice of ISP model, the position angles are much more coherent between mid–eclipse and 3rd contact when the polarization also increased (Figs. 6.13 & 6.14). Scattering from the disk material during eclipse
increases the signal and becomes the dominant source of polarization, overwhelming the underlying variable intrinsic (OOE) contribution. We observe large variations (±40°) in out-of-eclipse PA but only small variations (±10°) around 90° in PA during eclipse. The scattering by disk material is geometry-dependent and produces polarized light with coherent position angles. Contrast that behavior (small PA variations around 90°) with the large variations in the out-of-eclipse (OOE) position angles (Fig. 6.14). The OOE polarization is much more variable in direction which implies a more variable geometry to the scattering. This is further evidence that at least two variable components contribute to the observed OOE polarization.

6.6 Discussion

6.6.1 Out-of-eclipse

Polarimetric observations show that the ε Aurigae system exhibits persistent low level intrinsic polarization with periodic increases in polarization. The variability has been noted by other observers but the intrinsic component is quantified here for the first time. Changes to the degree of polarization appear over timescales as short as a few months (compare 1990–10–08 with 1990–12–02, Fig. 6.8 and Fig. 6.9). The position angle of intrinsic continuum polarization varies from around 70° to near 110° in the F0 star frame of reference but appears coherent by epoch across visible wavelengths in spectra and in broadband filter data (compare Figs. 6.9 and 6.12).

HPOL observations show that intrinsic continuum polarization peaks shortward of the B band zero point wavelength (4363 Å). The wavelength-dependent polarization is generally persistent but is more pronounced when the intrinsic polarization is largest (>3σ) across all visible wavelengths. Kloppenborg et al. (2012) noted that out-of-eclipse brightness variations were slightly wavelength dependent with the
strongest variations in the $U$ band and with decreasing amplitudes toward longer wavelengths.

We present the change in polarized flux and total flux relative to the HPOL observation of 1992–02–27 in Figure 6.4. We observe an increase in polarized flux from the adopted zero point epoch (intrinsic $\%p = 0$) regardless of whether or not the total flux increased or decreased relative to that observation. This is another indication that the chosen epoch has low/no intrinsic polarization and may therefore serve as a model for the ISP. We observe that the star appears to trend brighter between phases 1.35 and 1.37 (RJDs 48172 to 48299), but polarized flux is variable during that time. We observe no trend in polarized flux with orbit, but our coverage is sparse. The change in polarized flux in $B$ band appears to correlate with the $B$ band magnitude; the polarized flux is strongest in $B$ band when the system is relatively brighter in $B$ band.

Scattering position angles in out–of–eclipse HPOL observations vary from around 90° in the stellar frame of reference using the ISP Case A, or about 135° using the ISP Case C Figure 6.12. An intrinsic PA of 90° is inconsistent with optically thin Thomson scattering from free electrons or scattering from small dust grains when the distribution is aligned perpendicular to the likely orbital axis of the system (e.g. Bjorkman, 2012).

### 6.6.2 Balmer index polarization

We observe variability in the (largely intrinsic) Balmer index in HPOL observations of $\varepsilon$ Aurigae. We do not find a linear trend in the data, which if present would indicate a dominant underlying geometry, therefore we must conclude that more than one source of scattering exists in the system. We observe variability in both
Q and U, including short–term reversals in the direction of the variability (toward both increasing and decreasing PA), evident in Fig. 6.6 and Fig. 6.17.

6.6.3 Eclipse

Scattering position angles observed in broadband filters during eclipse vary around 90° in the stellar frame of reference. Scattering at 90° is inconsistent with optically thin Thomson scattering from free electrons or dust scattering from small grains when the distribution is aligned perpendicular to the likely orbital axis of the system. Wavelength–dependent scattering at 90° to the presumed orbital axis may indicate scattering from large ($x > 1$) dust grains in the disk or additional absorption of singly or multiply scattered photons. For example, a polarization position angle flip of 90° (resulting in a PA parallel to the disk axis) has been observed in Herbig Ae/Be stars and in young stellar objects (YSO) with optically thick circumstellar disks (Fischer et al., 1994).

A scattering position angle near 90° is consistent with electron scattering, or dust scattering from small grains, in polar scattering geometries. A large opacity along the equatorial axis may remove most of the equatorially–scattered photons, leaving only those photons scattered from above and below the disk to reach our line–of–sight, giving the apparent polarization signal typical of a jet (e.g. Voshchin-nikov and Karjukin, 1994; Wood et al., 1996b; Bjorkman, 2012).

The grayness of the eclipse (e.g. Lissauer et al., 1996) and the observed continuum polarization position angle (near 90°) both suggest light scattering at large ($x > 1$) dust grains as the primary source of polarization during eclipse. In addition, the disk was modeled with a thin, not extended, outer layer (Hoard et al., 2012, 0.1 AU above and below an opaque disk of 0.76 AU). Models used in the direct
interferometric imaging of \( \varepsilon \) Aurigae also suggested the disk is a debris disk rather than a young stellar object Kloppenborg et al. (2010).

### 6.7 Conclusions

We find the following characteristics of the out–of–eclipse continuum polarization independent of the choice of ISP model.

- The observed polarization is largely interstellar.

- The intrinsic polarization is variable and contributes a few tenths of a percent to the total observed polarization.

- The intrinsic continuum polarization is sometimes wavelength–dependent.

- Wavelength–dependent polarization peaks in the blue (\( \sim 4000\)Å in spectra or shortward of the \( B \) band zero point wavelength (4363Å) in filters). Wavelength dependence is not an artifact of the reduction and can be observed in combined (interstellar + intrinsic) data.

- Intrinsic polarization position angles vary between observations, but are consistent across visible wavelengths at HPOL resolution.

- We do not find a preferred direction for scattering in polarization measured by the (F0 star) Balmer jump index. More than one source contributes to the observed intrinsic polarization.

- We find an intrinsic polarization position angle in a recent Balmer jump index measurement very different from the average 117\( ^\circ \) of prior HPOL observations (PA 33\( ^\circ \) observed on 2012–10–22 at orbital phase 0.17).
We observe the following in eclipse.

- An increase in broadband polarization is coincident with the photometric eclipse. F0 star light scattering from disk material contributes to the increased polarization.

- The increase in polarization observed during eclipse is on average a few tenths of a percent greater than the maximum polarization observed out-of-eclipse.

- An increase in polarization above the eclipse average is observed for a short time near 3rd contact in both recent eclipses (1982–1984 and 2009–2011).

- The intrinsic continuum polarization position angle is near 90° from mid-eclipse to 3rd contact. Scattering at 90° is inconsistent with optically thin scattering from small dust grains given the known geometry of the system. This implies the polarization arises from scattering at large dust grains.

- The out-of-eclipse variability in continuum polarization is observed during eclipse. At least some of the continuum polarization may be attributed to the F0 star.

Our adopted \( \%p \) for the interstellar polarization (Case A; \( \%p = 1.97 \pm 0.02, \) \( \text{PA} = 145.0^\circ \pm 0.3^\circ \) in \( V \) band and adopting systematic uncertainties) supports a distance at least as great as the distance of the polarimetric reference star HD 32446 (~1 kpc McDonald et al., 2012) and is consistent with the m–M of 10.96 (compared to m–M of 9.03 for HD 32446, Table 6.11) suggested by Coyne (1972). The adopted degree of interstellar polarization along the line-of-sight is consistent with a supergiant designation for the F0 star in the \( \varepsilon \) Aurigae system. Observations of stars with similar distance and closer proximity to \( \varepsilon \) Aurigae could reduce the uncertainty in the adopted \( \%p \) and PA of the ISP along the line-of-sight.
Further modeling of the $\varepsilon$ Aurigae system is needed to explain wavelength-dependent scattering at intrinsic position angles largely oriented perpendicular to the presumed orbital axis of the system. Our group is actively engaged in developing 3D models of the system (e.g. Pearson and Stencel, 2015) which may shed some light on the observed phenomenon.

6.8 Afterword

This work is in preparation for publication: Kathleen Geise, Jennifer L. Hoffman, Robert E. Stencel, Gary Cole, James W. Davidson Jr., 2015.
6.9 Supplement

6.9.1 Interstellar polarization

We evaluated three cases to characterize the interstellar polarization along the $\varepsilon$ Aurigae line–of–sight: Cases A, B and C.

**Case A** assumes that the degree of polarization observed in the $\varepsilon$ Aurigae system varies aperiodically as noted by others, but that the position angle is unlikely to vary widely on the timescales of the observations ($\sim$one month to several years). A further assumption is that the system may sometimes be observed in a state which yields no net observable intrinsic linear polarization. The direction of decreasing intrinsic $%p$ could be characterized by assuming the position angles are not varying. In this case, the interstellar polarization may be represented by the $%p$ and position angle from an epoch of observed least–polarization, and the interstellar contribution may be fully–characterized by a Serkowski law fit to the observed spectrum from this epoch.

Similar to Case A, **Case B** assumes that the intrinsic position angle does not vary widely during the observations; but in this case, the system does not exhibit a state of zero intrinsic polarization. The intrinsic polarization position angle may be determined from the time–variability of the broadband data, for example, but the zero point of the degree of intrinsic polarization is ambiguous and hence, the intercept of the interstellar contribution in the $qu$–plane is also ambiguous. We may attempt to constrain the position angle of the interstellar contribution using observations of field stars, for example, and infer the degree of interstellar polarization as the point of intercept of these angles in the $qu$–plane (see discussion, below).
A model for the interstellar contribution may be developed using the Serkowski law and the inferred $p$ and PA from the intercept.

Finally, for **Case C**, we do not constrain the position angle to be invariant over the timespan of the observations. In this case, the inferred $p$ and position angle derived from observations of the polarization change across the Balmer jump may be used as a model for interstellar polarization (see discussion, below).

**Case A**

Linear least–squares fits to unrotated HPOL broadband data (Fig. 6.3) and to $B, V, R$ band polarization observations taken during the most recent eclipse (Fig. 6.18) indicate that decreasing polarization is associated with increasing position angle (increasing $q$ and less negative $u$) along the lines fit to the data. The Serkowski law fits to HPOL spectra (Table 6.6) suggest that minimum linear polarization was observed on 1991–02–12 and 1992–02–17. Similarly, polarization minima were observed in $V$ band (and all other artificial filter bands) on 1991–02–12 and 1992–02–17 (Table 6.3). The preferred epoch of least polarization is 1992–02–17 in this case because it represents the greatest position angle and the smallest degree of polarization in the broadband observations ($p = 1.97 \pm 0.02$, $PA = 145.0^\circ \pm 0.3^\circ$, adopting systematic uncertainties). Choosing any other epoch to represent the interstellar polarization would allow greater variability in the resultant intrinsic polarization position angle.

**Case B**

In this scenario, the first constraint for the interstellar polarization is provided by $B, V, R$ band polarization observations taken during the most recent eclipse (Cole, 2012). We plotted each filter separately and noted a linear trend in the data,
indicating a persistent preferred geometry for scattering in the system, related to
the observed orientation on the sky (see also Cole, 2012, Figs. 4 and 5). We fit a line
to the observations and noted that the polarization decreased after eclipse along the
line toward increasing position angle (Fig. 6.18). As the intrinsic polarization de-
creased after eclipse, the underlying interstellar polarization was revealed to reside
at a position angle greater than the position angles observed during eclipse (median
141° in V band). The V band eclipse observations represent the lower bound of pos-
sible ISP position angles along the ε Aurigae line–of–sight (interstellar PA >141°).

We plotted polarization in %q and %u for intrinsically unpolarized stars located
in the vicinity of ε Aurigae (Table 6.11). The field stars represent a measure of the
interstellar polarization along lines–of–sight similar to that of ε Aurigae for stars
of varying distances. The interstellar contribution may be represented by a vector
in the qu–plane which intersects the lines fit to the broadband data, representing
the intrinsic PA, where the length of the vector represents the degree of interstellar
polarization and the angle measured from the positive q–axis is 2θ, or twice the
position angle, θ, measured east of north on the sky. The interstellar contribution
originates at the origin (0,0) of the qu–plane and intersects the line for each band,
following a Serkowski law. The position angle should be the same in each band
(change only slightly with wavelength).

The interstellar contribution may be constrained by the linear least–squares fits
to %q and %u where the V band polarization is greater than all other filter bands.
The maximum interstellar polarization must then occur at PA < 150° (where the
linear fit to (%q ,%u) in V band equals the fit in R band, see Table 6.7). This
constraint is imposed by the Serkowski law.
Three of the unpolarized field stars (HD 32446, HD 33357, HD 30353) had a position angle within the above constraints (141° < PA < 150°, see Table 6.11). We fixed the smallest position angle measured (HD 32446, PA 148°) and extrapolated the degree of polarization to allow the resultant vector to intercept the linear least-squares fit to the ε Aurigae V band observations (Fig. 6.19). The difference in polarization may be explained by a presumed difference in distance (assuming ε Aurigae is farther away; compare m−M, Table 6.11). The interstellar polarization may be further constrained by assuming that this fit (%q = 0.82, %u = −1.67, %p = 1.86, P.A. = 148°, no uncertainties given in the original observation) represents the upper bound of possible interstellar polarization along the ε Aurigae line-of-sight (interstellar PA < 148°). Any larger interstellar PA would yield greater intrinsic %p, not implied by the observed variability.

A possible model for the ISP may be estimated using the maximum ISP derived from the field stars, as above, where %q = 0.82, %u = −1.67, %p = 1.86, PA = 148° and adopting typical systematic uncertainties of 0.02% for %q and %u (compare to the uncertainty in the linear fit for parameter A of 0.01% to 0.03%, Table 6.7).

**Case C**

We calculated the position angle of the Balmer index using the resultant %q and %u after differencing the Balmer indices BJ+ and BJ−. The Balmer index position angles varied over the range 127° to 153° for observations spaced closely in time (∼1 year) and varied even more widely for observations spaced over a decade or more (see Table 6.9). Note that an uncertainty in the Balmer index of 0.03% (%p = 0.21) is the equivalent of an uncertainty in position angle of ∼4°, suggesting that the variability in the Balmer index is real and significant (> 3σ).
The Balmer index PA measures the intrinsic continuum polarization position angles in the system. The large variability in the Balmer index suggests (1) there is more than one geometry contributing to scattering, even when the system is observed out–of–eclipse; and (2) at least one of the sources of scattering is variable. Henson (1989) reached a similar conclusion in his analysis of broadband polarimetric variability over 4 years of observations.

We adopted the five Reticon observations (1990–10–18 to 1992–02–27, see Table 6.2) as a representative sample of the “short–term” scattering behavior of the system. The Cousins–Glass–Johnson artificial $U$ band and $B$ band data span a similar range of wavelengths to the Balmer filters (BJ–$\lambda = 0.320 \, \mu m$ to $0.365 \, \mu m$; $U$ band $\lambda_{\text{eff}} = 0.366 \, \mu m$; $B$ band $\lambda_{\text{eff}} = 0.438 \, \mu m$, Bessell et al. (1998)). The $U$ band and $B$ band filters include contributions from both intrinsic and interstellar polarization, with the same PA for the interstellar component. Working backward, we differenced the Balmer index and each of the two filters to find an average $q$ and $u$ to represent the interstellar contribution. We then calculated the position angle to determine the third and final measure of interstellar polarization (PA = 143.5° ± 1.1°), assumed to be the same across all bands. Our last task was to deduce the magnitude of the interstellar polarization.

We note that the adopted ISP PA and the Balmer indices for the Reticon observations all lie within a similar range of angles in the $qu$–plane. The intrinsic polarization (a vector sum of more than one contribution) adds vectorially to the interstellar component originating at $(0, 0)$ to yield the observed polarization. Two scenarios presented themselves: (1) the intrinsic polarization is small in magnitude and combines vectorially along the same general direction as, or even orthogonally to, the interstellar polarization; or (2) the intrinsic polarization magnitude is large.
and combines vectorially in a direction generally opposite the interstellar polarization.

We consider scenario (1) to be the more likely behavior of the intrinsic polarization. Fig. 6.9 supports our interpretation in the following way. All the BJ+ (interstellar + intrinsic) filter data for the Reticon observations lie farther from the BJ− (largely interstellar) filter data in a region of greater %q, more negative %u, suggesting that the intrinsic components combined to yield a vector of small magnitude and with a position angle in roughly the same range of angles as the observed polarization. These small intrinsic polarizations then added to the interstellar polarization to create the resultant observed polarization.

We may construct a model of the interstellar polarization with an ISP B band value using the average difference calculated from the B band observations (%p_{ave} 1.77)^6 and a PA \sim 143°, or look for an appropriate BJ+ observation and assume that this observation is largely interstellar and could serve as an appropriate model.

Tables 6.6 and 6.7 suggest that the HPOL observation 1991–02–12 closely meets the criteria for selection, outlined above. Fig. 6.3 supports our choice of this observation as an epoch of minimum polarization because the vector length measured from (0,0) is smallest to the data point 1991–02–12 (filled circle) in each band. We scaled this observation to yield a B-band value of 1.77 (p_{max} = 1.85%) and used Serkowski law fit parameters to the spectrum (K = 1.01, \lambda_{max} = 0.5379, no rotation) as a model for the ISP. Note however, that selecting an interstellar polarization vector

---

^6Because we are concerned with the filters BJ+, BJ−, U band, and B band in this analysis, the maximum %p we could choose would be found by differencing the Balmer index with the B band. The maximum interstellar %p avoids over-estimating the intrinsic contribution, which we suspect is small.
with this epoch’s $p$ and PA results in a larger variation in the resultant intrinsic broadband position angles.

We chose Case A as the most likely description of the interstellar polarization (see Section 6.3.7).
<table>
<thead>
<tr>
<th>Parameter</th>
<th>$q = 0.75$</th>
<th>$q = 1.25$</th>
<th>[unit]</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d$</td>
<td>740[±99]</td>
<td>952[±127]</td>
<td>pc</td>
<td>1</td>
</tr>
<tr>
<td>$M_{F*}$</td>
<td>5.77</td>
<td>15.89</td>
<td>$M_\odot$</td>
<td>1</td>
</tr>
<tr>
<td>$M_{B*}$</td>
<td>7.69</td>
<td>12.71</td>
<td>$M_\odot$</td>
<td>1</td>
</tr>
<tr>
<td>$r_{\text{disk}}$</td>
<td>5.80</td>
<td>7.45</td>
<td>AU</td>
<td>1</td>
</tr>
<tr>
<td>$a_1 \sin i$</td>
<td>1835 [±19]</td>
<td>1835 [±19]</td>
<td>$10^6$ km</td>
<td>2</td>
</tr>
<tr>
<td>$e$</td>
<td>0.276 [±0.015]</td>
<td>0.276 [±0.015]</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>$a_{\text{Total}}$</td>
<td>21.47</td>
<td>27.60</td>
<td>AU</td>
<td>3</td>
</tr>
<tr>
<td>$a_1$</td>
<td>12.27</td>
<td>12.27</td>
<td>AU</td>
<td>4</td>
</tr>
<tr>
<td>$a_2$</td>
<td>9.20</td>
<td>15.33</td>
<td>AU</td>
<td>4</td>
</tr>
<tr>
<td>$r_1$ (periastron)</td>
<td>8.9</td>
<td>8.9</td>
<td>AU</td>
<td>4</td>
</tr>
<tr>
<td>$r_2$ (periastron)</td>
<td>6.7</td>
<td>11.1</td>
<td>AU</td>
<td>4</td>
</tr>
<tr>
<td>$r_{\text{Total}}$ (periastron)</td>
<td>15.6</td>
<td>20.0</td>
<td>AU</td>
<td>4</td>
</tr>
<tr>
<td>$d_{\text{disk}}^p$ (periastron)</td>
<td>9.8</td>
<td>12.6</td>
<td>AU</td>
<td>4</td>
</tr>
<tr>
<td>$r_1$ (apastron)</td>
<td>15.7</td>
<td>15.7</td>
<td>AU</td>
<td>4</td>
</tr>
<tr>
<td>$r_2$ (apastron)</td>
<td>11.7</td>
<td>19.6</td>
<td>AU</td>
<td>4</td>
</tr>
<tr>
<td>$r_{\text{Total}}$ (apastron)</td>
<td>27.4</td>
<td>35.3</td>
<td>AU</td>
<td>4</td>
</tr>
<tr>
<td>$d_{\text{disk}}^a$ (apastron)</td>
<td>21.6</td>
<td>27.9</td>
<td>AU</td>
<td>4</td>
</tr>
<tr>
<td>$r_{\text{Ave}}$ (Neptune)</td>
<td>30.1</td>
<td>⋯</td>
<td>AU</td>
<td>5</td>
</tr>
</tbody>
</table>

Note. — Orbital parameters for the ε Aurigae system for two mass ratios, $q$: $d$ is distance; $M_*$ are the stellar masses, where the F0 star is the adopted primary; $r_{\text{disk}}$ is the disk radius; $e$ is the eccentricity; $a_{\text{Total}}$ corresponds to the stellar separation for a circular orbit ($a_1 + a_2$); $a_1$ and $a_2$ are the orbital semi–major axes; $r_1$ and $r_2$ are the distances from the barycenter of the orbit, and $r_{\text{Total}}$ is the distance between the stars. The distance from the F0 star to the disk edge, $d_{\text{disk}}^p$, is $r_{\text{Total}}$ less the disk radius for each $q$. The average distance between Neptune and the Sun is given for scale.

1Pearson and Stencel (2015)
2Stefanik et al. (2010)
3Kloppenborg (2012)
4calculated this paper
5Online: http://hyperphysics.phy-astr.gsu.edu
Table 6.2. HPOL observations of $\varepsilon$ Aurigae

<table>
<thead>
<tr>
<th>Date</th>
<th>RJD</th>
<th>$\Delta$RJD$^a$</th>
<th>Detector</th>
<th>Phase$^b$</th>
<th>HRV$^b$ (km s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990–10–08$^c$</td>
<td>48172</td>
<td>1</td>
<td>Reticon</td>
<td>1.359</td>
<td>−13.6</td>
</tr>
<tr>
<td>1990–11–12$^c$</td>
<td>48207</td>
<td>36</td>
<td>Reticon</td>
<td>1.363</td>
<td>−13.6</td>
</tr>
<tr>
<td>1990–12–02$^c$</td>
<td>48227</td>
<td>56</td>
<td>Reticon</td>
<td>1.365</td>
<td>−13.6</td>
</tr>
<tr>
<td>1992–02–27$^c$</td>
<td>48679</td>
<td>508</td>
<td>Reticon</td>
<td>1.410</td>
<td>−13.0</td>
</tr>
<tr>
<td>1996–01–05$^c$</td>
<td>50087</td>
<td>1916</td>
<td>CCD</td>
<td>1.553</td>
<td>−8.4</td>
</tr>
<tr>
<td>2012–03–27</td>
<td>56013</td>
<td>7887</td>
<td>CCD</td>
<td>2.151</td>
<td>−6.4</td>
</tr>
<tr>
<td>2012–10–22</td>
<td>56222</td>
<td>8051</td>
<td>CCD</td>
<td>2.172</td>
<td>−8.1</td>
</tr>
<tr>
<td>2013–10–02</td>
<td>56567</td>
<td>8396</td>
<td>CCD</td>
<td>2.207</td>
<td>−10.5</td>
</tr>
</tbody>
</table>

$^a$We scaled RJD for plotting in log because our time series spans 23 years.

$^b$Heliocentric radial velocity (HRV) and phase are calculated using the ephemeris from Stefanik et al. (2010); RJD = HJD − 2,400,000. The first digit of the phase is the millennium of observation 1=(1990–2000), 2=2000+

$^c$These HPOL data are available online at http://www.sal.wisc.edu
Table 6.3: HPOL Synthetic UBVRI Filter Data for eps Aur

<table>
<thead>
<tr>
<th>Date/Filter</th>
<th>%Q</th>
<th>%U</th>
<th>%Err</th>
<th>%Pol</th>
<th>PA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990–10–08</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UX</td>
<td>0.5385</td>
<td>−1.7498</td>
<td>0.0089</td>
<td>1.8308</td>
<td>143.553</td>
</tr>
<tr>
<td>B</td>
<td>0.5832</td>
<td>−1.8842</td>
<td>0.0015</td>
<td>1.9724</td>
<td>143.599</td>
</tr>
<tr>
<td>V</td>
<td>0.6106</td>
<td>−1.9175</td>
<td>0.0012</td>
<td>2.0123</td>
<td>143.832</td>
</tr>
<tr>
<td>R</td>
<td>0.6106</td>
<td>−1.8192</td>
<td>0.0016</td>
<td>1.9189</td>
<td>144.276</td>
</tr>
<tr>
<td>I</td>
<td>0.6003</td>
<td>−1.6175</td>
<td>0.0076</td>
<td>1.7253</td>
<td>145.180</td>
</tr>
<tr>
<td>1990–11–12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UX</td>
<td>0.5965</td>
<td>−1.6953</td>
<td>0.0034</td>
<td>1.7972</td>
<td>144.692</td>
</tr>
<tr>
<td>B</td>
<td>0.6328</td>
<td>−1.8198</td>
<td>0.0007</td>
<td>1.9267</td>
<td>144.587</td>
</tr>
<tr>
<td>V</td>
<td>0.6560</td>
<td>−1.8806</td>
<td>0.0006</td>
<td>1.9918</td>
<td>144.615</td>
</tr>
<tr>
<td>R</td>
<td>0.6512</td>
<td>−1.8138</td>
<td>0.0008</td>
<td>1.9272</td>
<td>144.875</td>
</tr>
<tr>
<td>I</td>
<td>0.6374</td>
<td>−1.6265</td>
<td>0.0030</td>
<td>1.7470</td>
<td>145.700</td>
</tr>
<tr>
<td>1990–12–02</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UX</td>
<td>0.4695</td>
<td>−1.8079</td>
<td>0.0035</td>
<td>1.8678</td>
<td>142.280</td>
</tr>
<tr>
<td>B</td>
<td>0.4615</td>
<td>−1.9879</td>
<td>0.0007</td>
<td>2.0407</td>
<td>141.535</td>
</tr>
<tr>
<td>V</td>
<td>0.4995</td>
<td>−2.0080</td>
<td>0.0007</td>
<td>2.0692</td>
<td>141.985</td>
</tr>
<tr>
<td>R</td>
<td>0.5028</td>
<td>−1.9098</td>
<td>0.0008</td>
<td>1.9749</td>
<td>142.375</td>
</tr>
<tr>
<td>I</td>
<td>0.4740</td>
<td>−1.7139</td>
<td>0.0030</td>
<td>1.7783</td>
<td>142.730</td>
</tr>
<tr>
<td>1991–02–12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UX</td>
<td>0.4786</td>
<td>−1.6834</td>
<td>0.0070</td>
<td>1.7501</td>
<td>142.935</td>
</tr>
<tr>
<td>B</td>
<td>0.5237</td>
<td>−1.7995</td>
<td>0.0012</td>
<td>1.8742</td>
<td>143.113</td>
</tr>
<tr>
<td>V</td>
<td>0.5844</td>
<td>−1.8695</td>
<td>0.0011</td>
<td>1.9587</td>
<td>143.679</td>
</tr>
<tr>
<td>R</td>
<td>0.6054</td>
<td>−1.8019</td>
<td>0.0013</td>
<td>1.9009</td>
<td>144.285</td>
</tr>
<tr>
<td>I</td>
<td>0.6018</td>
<td>−1.6573</td>
<td>0.0050</td>
<td>1.7631</td>
<td>144.979</td>
</tr>
<tr>
<td>1992–02–27</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UX</td>
<td>0.6219</td>
<td>−1.6262</td>
<td>0.0107</td>
<td>1.7410</td>
<td>145.465</td>
</tr>
<tr>
<td>B</td>
<td>0.6731</td>
<td>−1.7702</td>
<td>0.0019</td>
<td>1.8939</td>
<td>145.409</td>
</tr>
<tr>
<td>V</td>
<td>0.6746</td>
<td>−1.8533</td>
<td>0.0014</td>
<td>1.9722</td>
<td>145.000</td>
</tr>
<tr>
<td>R</td>
<td>0.6751</td>
<td>−1.7905</td>
<td>0.0017</td>
<td>1.9136</td>
<td>145.330</td>
</tr>
<tr>
<td>I</td>
<td>0.6878</td>
<td>−1.6236</td>
<td>0.0070</td>
<td>1.7633</td>
<td>146.480</td>
</tr>
<tr>
<td>1996–01–05</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UX</td>
<td>0.6041</td>
<td>−1.7171</td>
<td>0.0161</td>
<td>1.8202</td>
<td>144.691</td>
</tr>
<tr>
<td>B</td>
<td>0.5822</td>
<td>−1.8999</td>
<td>0.0024</td>
<td>1.9871</td>
<td>143.518</td>
</tr>
<tr>
<td>V</td>
<td>0.6117</td>
<td>−1.9514</td>
<td>0.0012</td>
<td>2.0450</td>
<td>143.702</td>
</tr>
</tbody>
</table>

Continued on Next Page...
Table 6.3 – Continued

<table>
<thead>
<tr>
<th>Date/Filter&lt;sup&gt;a&lt;/sup&gt;</th>
<th>%Q</th>
<th>%U</th>
<th>%Err</th>
<th>%Pol</th>
<th>PA</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>0.6114</td>
<td>−1.8601</td>
<td>0.0008</td>
<td>1.9580</td>
<td>144.098</td>
</tr>
<tr>
<td>I</td>
<td>0.5408</td>
<td>−1.6191</td>
<td>0.0009</td>
<td>1.7070</td>
<td>144.235</td>
</tr>
<tr>
<td>2012–03–27</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UX</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>B</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>V</td>
<td>0.5191</td>
<td>−2.0229</td>
<td>0.0018</td>
<td>2.0885</td>
<td>142.196</td>
</tr>
<tr>
<td>R</td>
<td>0.5210</td>
<td>−1.9479</td>
<td>0.0009</td>
<td>2.0164</td>
<td>142.487</td>
</tr>
<tr>
<td>I</td>
<td>0.4971</td>
<td>−1.7575</td>
<td>0.0009</td>
<td>1.8264</td>
<td>142.897</td>
</tr>
<tr>
<td>2012–10–22</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UX</td>
<td>0.6256</td>
<td>−1.9346</td>
<td>0.0180</td>
<td>2.0332</td>
<td>143.960</td>
</tr>
<tr>
<td>B</td>
<td>0.6050</td>
<td>−1.9961</td>
<td>0.0021</td>
<td>2.0858</td>
<td>143.431</td>
</tr>
<tr>
<td>V</td>
<td>0.6468</td>
<td>−2.0439</td>
<td>0.0011</td>
<td>2.1439</td>
<td>143.780</td>
</tr>
<tr>
<td>R</td>
<td>0.6454</td>
<td>−1.9371</td>
<td>0.0008</td>
<td>2.0418</td>
<td>144.214</td>
</tr>
<tr>
<td>I</td>
<td>0.5825</td>
<td>−1.6758</td>
<td>0.0009</td>
<td>1.7742</td>
<td>144.583</td>
</tr>
<tr>
<td>2013–10–02</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UX</td>
<td>0.4616</td>
<td>−1.6556</td>
<td>0.1399</td>
<td>1.7188</td>
<td>142.790</td>
</tr>
<tr>
<td>B</td>
<td>0.4918</td>
<td>−1.8742</td>
<td>0.0025</td>
<td>1.9376</td>
<td>142.352</td>
</tr>
<tr>
<td>V</td>
<td>0.5890</td>
<td>−1.9351</td>
<td>0.0013</td>
<td>2.0227</td>
<td>144.465</td>
</tr>
<tr>
<td>R</td>
<td>0.5900</td>
<td>−1.8256</td>
<td>0.0008</td>
<td>1.9186</td>
<td>143.955</td>
</tr>
<tr>
<td>I</td>
<td>0.5374</td>
<td>−1.5565</td>
<td>0.0008</td>
<td>1.6467</td>
<td>144.524</td>
</tr>
</tbody>
</table>

Note: These data are HPOL observations of ε Aurigae. The data are available online at http://www.sal.wisc.edu/HPOL and in the FITS file headers of HPOL spectra.

<sup>a</sup>Reticon <i>I</i> band filter data include a falloff in instrument response. They are listed here for completeness but were not used in fitting.
Table 6.4. FCO observations of $\varepsilon$ Aurigae$^a$

<table>
<thead>
<tr>
<th>Date</th>
<th>RJD</th>
<th>Phase$^b$</th>
<th>HRV$^b$ (km s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1975–01–06</td>
<td>42418.6</td>
<td>1.778</td>
<td>5.6</td>
</tr>
<tr>
<td>1975–10–04</td>
<td>42689.8</td>
<td>1.805</td>
<td>7.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Date</th>
<th>Filter</th>
<th>%Q</th>
<th>%U</th>
<th>Unc %Q</th>
<th>%Pol</th>
<th>PA$^c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1975–01–06</td>
<td>U</td>
<td>0.330</td>
<td>−1.950</td>
<td>0.060</td>
<td>1.98</td>
<td>139.8</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>0.740</td>
<td>−2.020</td>
<td>0.030</td>
<td>2.15</td>
<td>145.1</td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>0.810</td>
<td>−1.980</td>
<td>0.040</td>
<td>2.14</td>
<td>146.1</td>
</tr>
<tr>
<td></td>
<td>R</td>
<td>0.780</td>
<td>−1.870</td>
<td>0.050</td>
<td>2.03</td>
<td>146.3</td>
</tr>
<tr>
<td>1975–10–04</td>
<td>B</td>
<td>0.830</td>
<td>−2.040</td>
<td>0.020</td>
<td>2.20</td>
<td>146.1</td>
</tr>
</tbody>
</table>

$^a$Data are from Elias et al. (2008); Flower and Cook Observatory, University of Pennsylvania. No uncertainties given.

$^b$Heliocentric radial velocity (HRV) and phase are calculated using the ephemeris from Stefanik et al. (2010); RJD = HJD−2,400,000. The first digit of the phase is the millennium of observation 1=(1990–2000), 2=2000+.

$^c$Position angles are calculated as described in Bagnulo et al. (2009) and range between 0° and 180°.
Table 6.5. Epsilon Aurigae Average Magnitudes

<table>
<thead>
<tr>
<th>Date</th>
<th>U band</th>
<th>B band</th>
<th>V band</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ave mag</td>
<td>Num Pts</td>
<td>Δm</td>
</tr>
<tr>
<td>1990–10–08</td>
<td>3.77</td>
<td>4</td>
<td>−0.04</td>
</tr>
<tr>
<td>1990–11–12</td>
<td>3.73</td>
<td>6</td>
<td>−0.07</td>
</tr>
<tr>
<td>1990–12–02</td>
<td>3.69</td>
<td>3</td>
<td>−0.11</td>
</tr>
<tr>
<td>1991–02–12</td>
<td>3.72</td>
<td>4</td>
<td>−0.08</td>
</tr>
<tr>
<td>1992–02–27</td>
<td>3.81</td>
<td>8</td>
<td>0.00</td>
</tr>
<tr>
<td>1996–01–05</td>
<td>3.69</td>
<td>5</td>
<td>−0.12</td>
</tr>
<tr>
<td>2012–03–27</td>
<td>···</td>
<td>···</td>
<td>···</td>
</tr>
<tr>
<td>2012–10–22</td>
<td>···</td>
<td>···</td>
<td>···</td>
</tr>
<tr>
<td>2013–10–02</td>
<td>···</td>
<td>···</td>
<td>···</td>
</tr>
</tbody>
</table>

aAverage magnitudes were calculated using V band photometric data from the American Association of Variable Star Observers (AAVSO). The averages were calculated using a rolling 7-day error weighted-average centered on the observation date. We estimate the uncertainty in average magnitude as ±0.01 mag.

bWe calculated the change in magnitude compared to the epoch of least polarization (1991–02–12, Section 6.3.7). Negative Δm indicates the star was brighter.
### Table 6.6. Serkowski law fit to HPOL spectra

<table>
<thead>
<tr>
<th>Date</th>
<th>q(_{\text{max}}) (%)</th>
<th>u(_{\text{max}}) (%)</th>
<th>p(_{\text{max}}) (%)</th>
<th>θ(_{0}) (°)</th>
<th>λ(_{\text{max}}) (μm)</th>
<th>K</th>
<th>θ(_{\text{max}}) (°)</th>
<th>(\frac{d\theta}{dx}) (°μm)</th>
<th>chisq</th>
<th>DOF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990–10–08</td>
<td>0.61</td>
<td>−1.93</td>
<td>2.02</td>
<td>⋯</td>
<td>0.5106</td>
<td>0.94</td>
<td>143.7</td>
<td>⋯</td>
<td>2.9</td>
<td></td>
</tr>
<tr>
<td>1990–11–12</td>
<td>0.63</td>
<td>−1.85</td>
<td>1.96</td>
<td>⋯</td>
<td>0.5286</td>
<td>0.96</td>
<td>144.4</td>
<td>⋯</td>
<td>4.0</td>
<td></td>
</tr>
<tr>
<td>1990–12–02</td>
<td>0.48</td>
<td>−2.03</td>
<td>2.08</td>
<td>⋯</td>
<td>0.5064</td>
<td>0.99</td>
<td>141.7</td>
<td>⋯</td>
<td>3.4</td>
<td></td>
</tr>
<tr>
<td>1991–02–12</td>
<td>0.63</td>
<td>−1.87</td>
<td>1.97</td>
<td>⋯</td>
<td>0.5382</td>
<td>1.00</td>
<td>144.3</td>
<td>⋯</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td>1992–02–27</td>
<td>0.66</td>
<td>−1.83</td>
<td>1.94</td>
<td>⋯</td>
<td>0.5370</td>
<td>0.95</td>
<td>145.0</td>
<td>⋯</td>
<td>2.6</td>
<td></td>
</tr>
<tr>
<td>1996–01–05</td>
<td>0.66</td>
<td>−1.97</td>
<td>2.07</td>
<td>⋯</td>
<td>0.5245</td>
<td>1.04</td>
<td>144.3</td>
<td>⋯</td>
<td>2.1</td>
<td></td>
</tr>
</tbody>
</table>

**No position angle rotation**

<table>
<thead>
<tr>
<th>Date</th>
<th>q(_{\text{max}}) (%)</th>
<th>u(_{\text{max}}) (%)</th>
<th>p(_{\text{max}}) (%)</th>
<th>θ(_{0}) (°)</th>
<th>λ(_{\text{max}}) (μm)</th>
<th>K</th>
<th>θ(_{\text{max}}) (°)</th>
<th>(\frac{d\theta}{dx}) (°μm)</th>
<th>chisq</th>
<th>DOF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990–10–08</td>
<td>1.14</td>
<td>−1.67</td>
<td>2.02</td>
<td>145.4</td>
<td>0.5098</td>
<td>0.86</td>
<td>152.0</td>
<td>−0.8</td>
<td>3.2</td>
<td></td>
</tr>
<tr>
<td>1990–11–12</td>
<td>0.33</td>
<td>−1.97</td>
<td>2.00</td>
<td>145.4</td>
<td>0.5290</td>
<td>0.88</td>
<td>139.8</td>
<td>−0.4</td>
<td>4.3</td>
<td></td>
</tr>
<tr>
<td>1990–12–02</td>
<td>0.48</td>
<td>−2.03</td>
<td>2.08</td>
<td>144.0</td>
<td>0.5042</td>
<td>0.85</td>
<td>141.6</td>
<td>−1.1</td>
<td>3.6</td>
<td></td>
</tr>
<tr>
<td>1991–02–12</td>
<td>0.71</td>
<td>−1.83</td>
<td>1.96</td>
<td>146.7</td>
<td>0.5396</td>
<td>0.91</td>
<td>145.6</td>
<td>−1.6</td>
<td>2.9</td>
<td></td>
</tr>
<tr>
<td>1992–02–27</td>
<td>0.69</td>
<td>−1.85</td>
<td>1.98</td>
<td>145.3</td>
<td>0.5380</td>
<td>0.90</td>
<td>145.3</td>
<td>−0.1</td>
<td>3.3</td>
<td></td>
</tr>
<tr>
<td>1996–01–05</td>
<td>0.08</td>
<td>−2.06</td>
<td>2.06</td>
<td>145.0</td>
<td>0.5035</td>
<td>0.85</td>
<td>136.1</td>
<td>−0.7</td>
<td>2.2</td>
<td></td>
</tr>
</tbody>
</table>

**With position angle rotation**

<table>
<thead>
<tr>
<th>Date</th>
<th>q(_{\text{max}}) (%)</th>
<th>u(_{\text{max}}) (%)</th>
<th>p(_{\text{max}}) (%)</th>
<th>θ(_{0}) (°)</th>
<th>λ(_{\text{max}}) (μm)</th>
<th>K</th>
<th>θ(_{\text{max}}) (°)</th>
<th>(\frac{d\theta}{dx}) (°μm)</th>
<th>chisq</th>
<th>DOF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990–10–08</td>
<td>1.14</td>
<td>−1.67</td>
<td>2.02</td>
<td>145.4</td>
<td>0.5098</td>
<td>0.86</td>
<td>152.0</td>
<td>−0.8</td>
<td>3.2</td>
<td></td>
</tr>
<tr>
<td>1990–11–12</td>
<td>0.33</td>
<td>−1.97</td>
<td>2.00</td>
<td>145.4</td>
<td>0.5290</td>
<td>0.88</td>
<td>139.8</td>
<td>−0.4</td>
<td>4.3</td>
<td></td>
</tr>
<tr>
<td>1990–12–02</td>
<td>0.48</td>
<td>−2.03</td>
<td>2.08</td>
<td>144.0</td>
<td>0.5042</td>
<td>0.85</td>
<td>141.6</td>
<td>−1.1</td>
<td>3.6</td>
<td></td>
</tr>
<tr>
<td>1991–02–12</td>
<td>0.71</td>
<td>−1.83</td>
<td>1.96</td>
<td>146.7</td>
<td>0.5396</td>
<td>0.91</td>
<td>145.6</td>
<td>−1.6</td>
<td>2.9</td>
<td></td>
</tr>
<tr>
<td>1992–02–27</td>
<td>0.69</td>
<td>−1.85</td>
<td>1.98</td>
<td>145.3</td>
<td>0.5380</td>
<td>0.90</td>
<td>145.3</td>
<td>−0.1</td>
<td>3.3</td>
<td></td>
</tr>
<tr>
<td>1996–01–05</td>
<td>0.08</td>
<td>−2.06</td>
<td>2.06</td>
<td>145.0</td>
<td>0.5035</td>
<td>0.85</td>
<td>136.1</td>
<td>−0.7</td>
<td>2.2</td>
<td></td>
</tr>
</tbody>
</table>

\(a\) Free parameters of the fit were \(p_{\text{max}}\), \(K\), \(\lambda_{\text{max}}\).

Uncertainties: \(q_{\text{max}} \approx u_{\text{max}} \approx p_{\text{max}} \approx 0.002\%, \theta_{\text{max}} < 1^\circ\), \(K = 0.04\), \(\lambda_{\text{max}} \approx 20\text{ Å}\)

\(b\) Free parameters of the fit were \(p_{\text{max}}\), \(\theta_{0}\), \(\lambda_{\text{max}}\), \(\frac{d\theta}{dx}\) (see text).

Uncertainties as above, except \(\theta_{0} < 1^\circ\), \(\frac{d\theta}{dx} = 0.1^\circ\mu\text{m}^{-1}\).
Table 6.7. Linear fits to broadband filter data

<table>
<thead>
<tr>
<th>Filter</th>
<th>A</th>
<th>B</th>
<th>Unc A</th>
<th>Unc B</th>
<th>θ</th>
<th>Unc θa</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPOL synthetic $UBVR$ filter data$^b$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UX</td>
<td>-2.26</td>
<td>0.97</td>
<td>0.03</td>
<td>0.06</td>
<td>22.0</td>
<td>3.4</td>
</tr>
<tr>
<td>B</td>
<td>-2.58</td>
<td>1.28</td>
<td>0.01</td>
<td>0.02</td>
<td>26.0</td>
<td>1.1</td>
</tr>
<tr>
<td>V</td>
<td>-2.67</td>
<td>1.22</td>
<td>0.01</td>
<td>0.01</td>
<td>25.3</td>
<td>0.6</td>
</tr>
<tr>
<td>R</td>
<td>-2.49</td>
<td>1.03</td>
<td>0.01</td>
<td>0.01</td>
<td>23.9</td>
<td>0.6</td>
</tr>
<tr>
<td>Broadband $BVR$$^c$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>-2.47</td>
<td>1.20</td>
<td>0.03</td>
<td>0.08</td>
<td>25.1</td>
<td>4.6</td>
</tr>
<tr>
<td>V</td>
<td>-2.61</td>
<td>1.28</td>
<td>0.04</td>
<td>0.11</td>
<td>26.0</td>
<td>6.3</td>
</tr>
<tr>
<td>R</td>
<td>-2.48</td>
<td>0.91</td>
<td>0.04</td>
<td>0.09</td>
<td>21.1</td>
<td>5.2</td>
</tr>
</tbody>
</table>

$^a$The uncertainty in position angle was calculated using the uncertainty in the slope of the fit, parameter B, using Eqn. 6.3 (see text).

$^b$These fits include all out–of–eclipse HPOL artificial filter observations, see Table 6.3. We fit a linear regression model $y = A + Bx$ to data plotted in the Q–U plane.

$^c$These fits are Cole (2012) eclipse observations RJD 5145 to RJD 5800.
Table 6.8. HPOL systematic broadband filter uncertainties

<table>
<thead>
<tr>
<th>Date</th>
<th>U band</th>
<th>B band</th>
<th>V band</th>
<th>R band</th>
<th>I band(^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%Err</td>
<td>%Err</td>
<td>%Err</td>
<td>%Err</td>
<td>%Err</td>
</tr>
<tr>
<td>1990–10–08</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
</tr>
<tr>
<td>1990–11–12</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
</tr>
<tr>
<td>1990–12–02</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
</tr>
<tr>
<td>1991–02–12</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
</tr>
<tr>
<td>1992–02–27</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
</tr>
<tr>
<td>1996–01–05</td>
<td>0.060</td>
<td>0.030</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
</tr>
<tr>
<td>2012–03–27</td>
<td>0.075</td>
<td>0.011</td>
<td>0.009</td>
<td>0.006</td>
<td>0.010</td>
</tr>
<tr>
<td>2012–10–22</td>
<td>0.060</td>
<td>0.008</td>
<td>0.010</td>
<td>0.006</td>
<td>0.011</td>
</tr>
<tr>
<td>2013–10–02</td>
<td>0.060</td>
<td>0.011</td>
<td>0.009</td>
<td>0.002</td>
<td>0.010</td>
</tr>
</tbody>
</table>

Note. — Systematic uncertainties were adopted in this analysis, except for linear fits to broadband filters where an equal weighting of 0.02% uncertainty was applied to both Reticon and CCD data.

\(^a\)Reticon I band filter data include a falloff in instrument response. They are listed here for completeness but were not used in analysis.
Table 6.9: HPOL Synthetic Balmer Jump Filter Data

<table>
<thead>
<tr>
<th>Date/Filter</th>
<th>%Q</th>
<th>%U</th>
<th>%Err</th>
<th>%Pol</th>
<th>PA</th>
<th>Rot PA&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990–10–08</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BJ+</td>
<td>0.5661</td>
<td>−1.8202</td>
<td>0.0043</td>
<td>1.9062</td>
<td>143.638</td>
<td></td>
</tr>
<tr>
<td>BJ−</td>
<td>0.4542</td>
<td>−1.6428</td>
<td>0.0308</td>
<td>1.7044</td>
<td>142.727</td>
<td></td>
</tr>
<tr>
<td>Index</td>
<td>0.1119</td>
<td>−0.1774</td>
<td>0.0311</td>
<td>0.2097</td>
<td>151.129</td>
<td>124.1</td>
</tr>
<tr>
<td>1990–11–12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BJ+</td>
<td>0.6161</td>
<td>−1.7426</td>
<td>0.0020</td>
<td>1.8484</td>
<td>144.736</td>
<td></td>
</tr>
<tr>
<td>BJ−</td>
<td>0.5993</td>
<td>−1.6414</td>
<td>0.0109</td>
<td>1.7474</td>
<td>145.030</td>
<td></td>
</tr>
<tr>
<td>Index</td>
<td>0.0168</td>
<td>−0.1013</td>
<td>0.0110</td>
<td>0.1026</td>
<td>139.706</td>
<td>112.7</td>
</tr>
<tr>
<td>1990–12–02</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BJ+</td>
<td>0.4439</td>
<td>−1.9167</td>
<td>0.0020</td>
<td>1.9675</td>
<td>141.520</td>
<td></td>
</tr>
<tr>
<td>BJ−</td>
<td>0.5259</td>
<td>−1.6315</td>
<td>0.0107</td>
<td>1.7141</td>
<td>143.933</td>
<td></td>
</tr>
<tr>
<td>Index</td>
<td>−0.0820</td>
<td>−0.2853</td>
<td>0.0109</td>
<td>0.2968</td>
<td>126.982</td>
<td>100.0</td>
</tr>
<tr>
<td>1991–02–12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BJ+</td>
<td>0.4857</td>
<td>−1.7078</td>
<td>0.0033</td>
<td>1.7755</td>
<td>142.938</td>
<td></td>
</tr>
<tr>
<td>BJ−</td>
<td>0.4466</td>
<td>−1.6529</td>
<td>0.0232</td>
<td>1.7122</td>
<td>142.560</td>
<td></td>
</tr>
<tr>
<td>Index</td>
<td>0.0391</td>
<td>−0.549</td>
<td>0.0234</td>
<td>0.674</td>
<td>152.732</td>
<td>125.7</td>
</tr>
<tr>
<td>1992–02–27</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BJ+</td>
<td>0.6846</td>
<td>−1.6731</td>
<td>0.0058</td>
<td>1.8078</td>
<td>146.127</td>
<td></td>
</tr>
<tr>
<td>BJ−</td>
<td>0.4804</td>
<td>−1.5167</td>
<td>0.0358</td>
<td>1.5910</td>
<td>143.787</td>
<td></td>
</tr>
<tr>
<td>Index</td>
<td>0.2043</td>
<td>−0.1564</td>
<td>0.0363</td>
<td>0.2573</td>
<td>161.276</td>
<td>134.3</td>
</tr>
<tr>
<td>1996–01–05</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BJ+</td>
<td>0.5786</td>
<td>−1.8310</td>
<td>0.0063</td>
<td>1.9203</td>
<td>143.768</td>
<td></td>
</tr>
<tr>
<td>BJ−</td>
<td>0.6835</td>
<td>−1.2912</td>
<td>0.0770</td>
<td>1.4609</td>
<td>148.947</td>
<td></td>
</tr>
<tr>
<td>Index</td>
<td>−0.1049</td>
<td>−0.5398</td>
<td>0.0772</td>
<td>0.5499</td>
<td>129.504</td>
<td>102.5</td>
</tr>
<tr>
<td>2012–10–22</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BJ+</td>
<td>0.5632</td>
<td>−1.9410</td>
<td>0.0048</td>
<td>1.9952</td>
<td>143.199</td>
<td></td>
</tr>
<tr>
<td>BJ−</td>
<td>0.6731</td>
<td>−2.3446</td>
<td>0.1045</td>
<td>2.4818</td>
<td>144.569</td>
<td></td>
</tr>
<tr>
<td>Index</td>
<td>−0.2505</td>
<td>0.4306</td>
<td>0.1046</td>
<td>0.4982</td>
<td>60.094</td>
<td>33.1</td>
</tr>
</tbody>
</table>

Note: These are synthetic filter data from above (BJ+) and below (BJ−) the Balmer jump.

<sup>a</sup>Rotated 27° into stellar frame of reference using a rotation matrix (e.g. Bagnulo et al., 2009).
Table 6.10: Intrinsic polarization

<table>
<thead>
<tr>
<th>Date/Filter</th>
<th>Case A</th>
<th>Case C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%Pol</td>
<td>Unc PA</td>
</tr>
<tr>
<td></td>
<td>%Pol</td>
<td>(deg)</td>
</tr>
<tr>
<td>1990–10–08</td>
<td></td>
<td></td>
</tr>
<tr>
<td>U</td>
<td>0.15</td>
<td>0.02</td>
</tr>
<tr>
<td>B</td>
<td>0.15</td>
<td>0.02</td>
</tr>
<tr>
<td>V</td>
<td>0.09</td>
<td>0.02</td>
</tr>
<tr>
<td>R</td>
<td>0.07</td>
<td>0.02</td>
</tr>
<tr>
<td>1990–10–08</td>
<td></td>
<td></td>
</tr>
<tr>
<td>U</td>
<td>0.07</td>
<td>0.02</td>
</tr>
<tr>
<td>B</td>
<td>0.06</td>
<td>0.02</td>
</tr>
<tr>
<td>V</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>R</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>1990–10–08</td>
<td></td>
<td></td>
</tr>
<tr>
<td>U</td>
<td>0.24</td>
<td>0.02</td>
</tr>
<tr>
<td>B</td>
<td>0.30</td>
<td>0.02</td>
</tr>
<tr>
<td>V</td>
<td>0.23</td>
<td>0.02</td>
</tr>
<tr>
<td>R</td>
<td>0.21</td>
<td>0.02</td>
</tr>
<tr>
<td>1990–10–08</td>
<td></td>
<td></td>
</tr>
<tr>
<td>U</td>
<td>0.15</td>
<td>0.02</td>
</tr>
<tr>
<td>B</td>
<td>0.15</td>
<td>0.02</td>
</tr>
<tr>
<td>V</td>
<td>0.09</td>
<td>0.02</td>
</tr>
<tr>
<td>R</td>
<td>0.07</td>
<td>0.02</td>
</tr>
<tr>
<td>1990–10–08</td>
<td></td>
<td></td>
</tr>
<tr>
<td>U</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>B</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>V</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>R</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>1990–10–08</td>
<td></td>
<td></td>
</tr>
<tr>
<td>U</td>
<td>0.09</td>
<td>0.03</td>
</tr>
<tr>
<td>B</td>
<td>0.16</td>
<td>0.02</td>
</tr>
<tr>
<td>V</td>
<td>0.12</td>
<td>0.02</td>
</tr>
<tr>
<td>R</td>
<td>0.09</td>
<td>0.02</td>
</tr>
<tr>
<td>1990–10–08</td>
<td></td>
<td></td>
</tr>
<tr>
<td>U</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>B</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>V</td>
<td>0.23</td>
<td>0.02</td>
</tr>
<tr>
<td>R</td>
<td>0.22</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Continued on Next Page...
Table 6.10 – Continued

<table>
<thead>
<tr>
<th>Date/Filter</th>
<th>Case A</th>
<th>Case C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%Pol Unc PA</td>
<td>%Pol Unc PA</td>
</tr>
<tr>
<td></td>
<td>%Pol (deg)</td>
<td>Unc (deg)</td>
</tr>
<tr>
<td>1990–10–08</td>
<td>0.44 0.03 118.6 1.8</td>
<td>0.31 0.02 116.0 1.9</td>
</tr>
<tr>
<td>U</td>
<td>0.24 0.02 99.6 2.4</td>
<td>0.29 0.02 118.6 2.0</td>
</tr>
<tr>
<td>B</td>
<td>0.19 0.02 103.9 3.0</td>
<td>0.25 0.02 122.4 2.3</td>
</tr>
<tr>
<td>V</td>
<td>0.15 0.02 102.2 3.8</td>
<td>0.16 0.14 68.2 24.9</td>
</tr>
<tr>
<td>R</td>
<td>0.21 0.02 77.9 2.8</td>
<td>0.18 0.02 103.7 3.2</td>
</tr>
<tr>
<td>1990–10–08</td>
<td>0.19 0.02 84.9 4.8</td>
<td>0.17 0.02 116.1 3.4</td>
</tr>
<tr>
<td>U</td>
<td>0.09 0.02 74.1 6.2</td>
<td>0.12 0.02 123.7 4.7</td>
</tr>
</tbody>
</table>

Note: The data presented here are the intrinsic polarization and position angles for synthetic broadband filter data after removing a model for interstellar polarization. Two models for interstellar polarization are compared, Case A and Case C (see Appendix for a description of the models).
Table 6.11. Polarization of stars in the vicinity of $\varepsilon$ Aurigae

<table>
<thead>
<tr>
<th>Stars</th>
<th>$\Delta$ (deg)</th>
<th>Sp</th>
<th>m–M</th>
<th>%Pol</th>
<th>$\theta_e$ (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+43°1168</td>
<td>0.1</td>
<td>B9Iab</td>
<td>13.0</td>
<td>5.7</td>
<td>137</td>
</tr>
<tr>
<td>HD 31617</td>
<td>0.8</td>
<td>B2IV</td>
<td>9.7</td>
<td>1.9</td>
<td>164</td>
</tr>
<tr>
<td>HD 32446</td>
<td>1.5</td>
<td>B5III</td>
<td>9.3</td>
<td>1.4</td>
<td>148</td>
</tr>
<tr>
<td>HD 30650</td>
<td>2.6</td>
<td>B7V</td>
<td>7.6</td>
<td>1.3</td>
<td>178</td>
</tr>
<tr>
<td>+41°1031</td>
<td>2.6</td>
<td>…</td>
<td>…</td>
<td>1.2</td>
<td>150</td>
</tr>
<tr>
<td>HD 32630</td>
<td>2.9</td>
<td>B3V</td>
<td>4.9</td>
<td>0.4</td>
<td>177</td>
</tr>
<tr>
<td>HD 33357</td>
<td>3.0</td>
<td>B1(V)</td>
<td>10.7</td>
<td>2.2</td>
<td>149</td>
</tr>
<tr>
<td>HD 30353</td>
<td>3.6</td>
<td>A5Iap</td>
<td>14.2</td>
<td>2.2</td>
<td>149</td>
</tr>
<tr>
<td>HD 33232</td>
<td>3.6</td>
<td>B3e</td>
<td>…</td>
<td>1.2</td>
<td>140</td>
</tr>
<tr>
<td>HD 33461</td>
<td>3.7</td>
<td>B3Vnn3</td>
<td>8.7</td>
<td>1.8</td>
<td>165</td>
</tr>
<tr>
<td>+40°1189</td>
<td>3.8</td>
<td>B2III</td>
<td>11.6</td>
<td>2.0</td>
<td>160</td>
</tr>
</tbody>
</table>

Additional stars$^c$

<table>
<thead>
<tr>
<th>Stars</th>
<th>$\Delta$ (deg)</th>
<th>Sp</th>
<th>m–M</th>
<th>%Pol</th>
</tr>
</thead>
<tbody>
<tr>
<td>HD 32328</td>
<td>0.3</td>
<td>B8V</td>
<td>…</td>
<td>…</td>
</tr>
<tr>
<td>HD 277197</td>
<td>0.3</td>
<td>B8V</td>
<td>…</td>
<td>…</td>
</tr>
<tr>
<td>HD 31894</td>
<td>0.4</td>
<td>B2IV–V</td>
<td>…</td>
<td>…</td>
</tr>
</tbody>
</table>

$^a$Coyne (1972), Table 2

$^b$From Hall (1958)

$^c$Guinan et al. (2012), Table 2
Figure 6.1: HPOL broadband artificial filter $\%p$ plotted by phase. $V$ band (green triangle), $B$ band (blue square), $R$ band (red circle), $U$ band (purple diamond). Each plot corresponds to a different range of phases. The first digit of the phase represents the millennium of observation (1=1990–2000; 2=2000+). Phases were calculated using ephemeris by Stefanik et al. (2010) and range between 0.0 and 1.0 with periastron at phase 0.0. In this formulation, mid–eclipse occurs at phase 0.09 and apastron at phase 0.5. Note the middle plot contains observations that span apaston. Wavelength–dependent polarization is evident in some observations when $\%p_B > \%p_R$ (see text).
Figure 6.2: HPOL broadband artificial filter position angle (PA) plotted by phase. Plotting symbols offset in phase for clarity. Symbols and phases as in Fig. 6.1. These unrotated data include contributions from both interstellar and intrinsic polarization. Purely interstellar polarization would exhibit the same position angle (PA) in all broadband filters. The 1990–11–12 observation at phase 1.363 and the 1992–02–27 observation at phase 1.410 have the most cohesive observed PA (144.4° and 145.0°, respectively).
Figure 6.4: Change in polarized flux (top) and total flux (bottom) relative to the HPOL observation of 1992–02–27 (red X, $\phi = 1.41$) plotted with equally spaced phases. U band (purple diamond), B band (blue square) and V band (green triangle) are shown. Phases are calculated using the ephemeris of Stefanik et al. (2010). The leading digit of the phase describes the millennium of the observation (1=1990–2000, 2=2000+). Apastron is at $\phi = 1.5$ on this scale. All epochs show an increase in polarized flux from the adopted zero point epoch (intrinsic $\% p = 0$) regardless of whether or not the total flux increased or decreased relative to that observation. The star appears to trend brighter between phases 1.35 and 1.37 (RJDs 48172 to 48299), but polarized flux is variable during that time. Note the change in polarized flux in B band appears to correlate with the B band magnitude; the polarized flux is strongest in B band when the system is relatively brighter (the change in flux is positive) in B band.
Figure 6.5: HPOL Balmer jump filter data plotted as QU–plot. Black circles are BJ+ data, blue circles are BJ- data and the resultant (BJ+ − BJ-) Balmer jump index data are the circles near (0, 0). Uncertainties are the systematic uncertainties listed in Table 6.9. The scatter in the Balmer jump index data indicate that there is likely more than one contribution to continuum polarization present in the data.
Figure 6.6: HPOL Balmer jump filter position angles by log \( \Delta RJD \), where day 1 begins at the first observation (1990–10–08). From left to right, the epochs are: 1990–10–08, 1990–11–12, 1990–12–02, 1991–02–12, 1992–02–27, 1996–01–05, 2012–01–22. On this scale, the BJ+ data (open black circle) and BJ− data (open blue circle) nearly overlap. The resultant BJ index position angle appears to vary around an average for several observations and then changes dramatically in the most recent observation (2012–10–22).
Figure 6.7: HPOL spectrum 1990–10–18 QU–plots. The observed ε Aurigae data are binned by uncertainties and plotted in black. A model of interstellar polarization is plotted in red (upper left). Those data are rotated by 27° into the stellar reference frame (upper right). The interstellar model was subtracted from the original data and the residual plotted in blue (lower left). The residual data were rotated into the stellar frame of reference (lower right). Note the residual data are not centered on (0,0) indicating intrinsic polarization present in the data with a position angle on the sky near 90°.
Figure 6.8: Intrinsic polarization by wavelength [Å] for all available HPOL spectra, except 1990–11–12 (null result) and 1992–02–27 (ISP model). A model fit for interstellar polarization (Case A) has been subtracted from the original binned data and the resulting data have been rotated into the stellar reference frame. Note the wavelength dependence of the polarization exhibited in these epochs.
Figure 6.9: Intrinsic position angle by wavelength [Å] for HPOL spectra from Fig. 6.8. A model fit for interstellar polarization (Case A) has been subtracted from the original data and the resulting data have been rotated into the stellar frame.
Figure 6.10: A comparison of intrinsic polarization from four HPOL synthetic filters (UBVR, magenta diamonds) with an intrinsic spectrum for the same epoch. Magenta lines are to guide the eye. The differences in binning are apparent for polarization data near U band filter wavelengths. Binning by uncertainty (black lines) placed most data shortward of ~3700 Å into large bins, whereas filter data were weighted by the filter bandpass. A model fit for interstellar polarization has been subtracted from the data and the resulting data have been rotated into the stellar frame. Wavelength–dependent polarization may be observed in both the spectra and the filter data. The polarization peaks shortward of the B band zero point wavelength (4363 Å).
Figure 6.11: Intrinsic polarization from HPOL synthetic UBVR filter data for ε Aurigae. A model fit for interstellar polarization (ISP Case A, left; ISP Case C, right) has been subtracted from the original data and the resulting data have been rotated into the stellar frame. Filled symbols are 1990 data, open symbols are recent observations. Symbols color-coded by filter. 1990–10–08 (triangle), 1990–11–12 (square), 1990–12–02 (diamond), 1991–02–12 (circle), 1992–02–27 (X), 1996–01–05 (star), 2012–03–27 (diamond), 2012–10–22 (circle), 2013–10–02 (triangle). Symbols are offset in wavelength for clarity. Note wavelength-dependent polarization present in most epochs.
Figure 6.12: Intrinsic polarization position angle from HPOL synthetic $UBVR$ filter data for $\varepsilon$ Aurigae. A model fit for interstellar polarization (ISP Case A, left; ISP Case C, right) has been subtracted from the original data and the resulting data have been rotated into the stellar frame. Filled symbols are 1990 data, open symbols are recent observations. Symbols color-coded by filter. 1990–10–08 (triangle), 1990–11–12 (square), 1990–12–02 (diamond), 1991–02–12 (circle), 1992–02–27 (X), 1996–01–05 (star), 2012–03–27 (diamond), 2012–10–22 (circle), 2013–10–02 (triangle). Symbols are offset in wavelength for clarity.
Figure 6.13: Intrinsic $V$ band linear polarization by phase for two eclipse cycles. Intrinsic polarization from the prior (1982–1984) eclipse (black diamonds) were calculated by subtracting a model for interstellar polarization from Henson (1989) data. Intrinsic polarization from the current (2009–2011) eclipse (blue circles) were calculated by subtracting ISP model Case A from Cole (2012) data. The underlying out–of–eclipse variability is also imprinted on the eclipse polarization. We observe an increase in polarization near 3rd contact during both eclipses (orbital phase 0.11).
Figure 6.14: Intrinsic V band linear polarization position angle by phase for two eclipse cycles. Symbols and data reductions as in Fig. 6.13. The underlying out-of-eclipse variability is also imprinted on the eclipse polarization. We observe an increase in polarization near 3rd contact during both eclipses (orbital phase 0.11), but the system does not exhibit a large change in PA during that time. Note the decreasing position angle after 3rd contact observed in the 1984–1986 eclipse, but not the recent eclipse. Intrinsic position angles are more variable after both eclipses.
Figure 6.15: Intrinsic $B$ band linear polarization by phase for two eclipse cycles. Intrinsic polarization from the prior (1982–1984) eclipse (black diamonds) were calculated by subtracting a model for interstellar polarization from Henson (1989) data. Intrinsic polarization from the current (2009–2011) eclipse (blue circles) were calculated by subtracting ISP model Case A from Cole (2012) data. The underlying out-of-eclipse variability is also imprinted on the eclipse polarization. We observe an increase in polarization near 3rd contact during both eclipses (orbital phase 0.11). The peak amplitude in $B$ band is larger than in $V$ band (Fig. 6.13).
Figure 6.16: Intrinsic $B$ band linear polarization position angle by phase for two eclipse cycles. Symbols and data reductions as in Fig. 6.15. The underlying out–of–eclipse variability is also imprinted on the eclipse polarization. We observe an increase in polarization near 3$^{rd}$ contact during both eclipses (orbital phase 0.11), but the system does not exhibit a large change in PA during that time. Note the decreasing position angle after 3$^{rd}$ contact observed in the 1984–1986 eclipse, but not the recent eclipse. Intrinsic position angles are more variable after both eclipses. Compare with $V$ band (Fig. 6.14).
Figure 6.17: Balmer jump index data rotated by 27° to align telescope north with the presumed rotation axis of the F0 star. The Balmer index is considered to be free of interstellar polarization. Uncertainties are derived from photon statistics. Arrows point from one observation to the next with red–tipped arrows demarcating the first three observations; remaining arrows black–tipped (1990–10–18, 1990–11–12*, 1990–12–02, 1991–02–12*, 1992–02–27, 1996–01–05, 2012–01–22). Notice the polarization variability spans multiple time scales, with the large variation (longest arrow) between two CCD observations spaced 16 years apart (phase 1.553 to phase 2.151, see Table 6.2). The changes in polarization occur in both $Q$ and $U$, suggesting more than one geometry contributes to the observed polarization. *Low or near–zero polarization observed in the Balmer index.
Figure 6.18: QU–plot of broadband filter data from mid–eclipse to 4th contact noted by a color–coded + symbol (blue, B band; green, V band; red, R band) (Cole, 2012). Transitional data for 90 days post–eclipse are black + symbols in each plot. Magenta X points are post–eclipse observations taken later than 90 days after eclipse. Note the linear trends in the data. Position angle increases and %p decreases along each line toward greater %q, less negative %u. These plots suggest that the interstellar polarization vector should be placed to the right of the eclipse data. The adopted point taken from HPOL observations is marked by a black triangle (Case A). Note B band is slightly reddened and R band slightly truncated in these data (Cole, 2012).
Figure 6.19: HPOL V band data illustrating interstellar polarization (ISP) Case B. A linear least–squares fit to unrotated HPOL V band data (asterisks) is plotted (green dashed line) and replotted through (0,0). The angle from the +Q axis to the dashed green line corresponds to $2\theta$, or twice the intrinsic polarization position angle on the sky. The results of the fit ($\theta = 26.8^\circ \pm 0.6^\circ$) are consistent with interferometric observations for the rotation of the system on the sky. The diamond symbol marks the perpendicular intercept to the linear least–squares fit (and the smallest possible ISP). The star symbol marks the position angle of nearby star HD 32446 with a vector magnitude that intercepts the V band fit, Case B. All points between the star and the intercept along the linear least–squares fit correspond to a smaller interstellar $%p$ and larger intrinsic $%p$; they are rejected from consideration (see text).
Chapter 7

Conclusions

7.1 Summary

Polarimetry has proved to be a useful tool when combined with spectroscopy in the analysis of the $\varepsilon$ Aurigae system. Like the Second Solar Spectrum for the Sun (Stenflo and Keller, 1997), the polarimetric spectrum of $\varepsilon$ Aurigae has deepened our understanding of the dynamics and physical processes that shape the outer stellar atmosphere. We discovered that the F0 star is persistently polarized in both the continuum and the lines; this tells us that some anisotropy must exist in the tenuous extended F0 star atmosphere. We know which lines are polarized and to what degree they are polarized. We also have some idea of the timescales of variability of the line polarization. Because spectral lines probe different layers of the stellar atmosphere, we may use this information to uncover physical mechanisms that contribute to the underlying anisotropy. The work presented here combined with future modeling of the system will further inform our understanding of stellar atmospheres in general, but also the atmosphere of our own star. Finally, the line polarization reaffirms that a stellar atmosphere is an amazing laboratory for the study of quantum physics.

This dissertation has revealed important new information about the atmosphere surrounding the eclipsing disk in the $\varepsilon$ Aurigae system. Resonance scattering at atomic species is the primary mechanism producing the observed line polarization. The atomic transitions are sensitive to temperatures and abundances and may be used as probes of the physical environment, especially for unresolved objects (such
as the gas in the disk). We used scattering behavior in both lines and continuum to isolate a morphological feature of the disk observed near 3rd contact. This information was carried in the polarimetric spectrum but was largely hidden in the flux spectrum. The two spectra together provided a more powerful analysis tool than either spectrum alone. Finally, our observations support results from models of optically thick disks that light scattering from rotating disk material may leave an unmistakeable fingerprint on polarization spectra. The characteristic antisymmetric Stokes $U$ profile was apparent in our ESPaDOnS data because we rotated Stokes $Q$ and Stokes $U$ into the stellar/disk frame of reference. We were fortunate that the $\varepsilon$ Aurigae disk has been imaged interferometrically and would like to point out that the $\varepsilon$ Aurigae disk deserves further study precisely because so much is currently known about the system, even without an accurate distance determination.

7.2 The Epsilon Aurigae system in light of the spectropolarimetric observations

The F0 star atmosphere has persistent asymmetries that contribute to line polarization observed out-of-eclipse. We observe variable line polarization in spectra taken from near periastron to more than a year after the most recent eclipse (orbital phases 0.926 to 0.178; Table 5.1). The polarization is primarily associated with the absorption line cores and shifts with the F0 star motion. The line core and peak in polarization fall at the line rest wavelength when adjusted for F0 star motion using the ephemeris of Stefanik et al. (2010) (Fig. 4.2). The F0 star atmosphere is tenuous, extended ($\log g < 1$), is not collisionally dominated and is best described using stellar models adjusted for NLTE effects (Castelli, 1978; Sadakane et al., 2010). The polarization likely arises from a region high in stellar atmosphere because it is present in medium strength and strong lines that form in different levels in the atmosphere, the polarization is associated with the line core which forms higher in
the atmosphere than the wings and the atmosphere is very extended. Low angles ($\sim 0^\circ$) for the line polarization suggest that the anisotropy is equatorial (Table 4.5). The line polarization is probably not a wind phenomenon because it is centered around the line rest velocities in the stellar frame of reference. Finally, the F0 star has been characterized as a non-radial pulsating star (Dubath et al., 2011) which may contribute to the observed polarization (Henson, 1989).

The F0 star is an evolved star and is capable of episodic mass loss to sustain a companion’s disk. Enhanced mass loss is possible during large amplitude oscillations, which may have been observed spectroscopically by ESPaDOnS on 2006–02–08 (section 4.5.2). The F0 star has a wind that contributes to mass loss (Ake, 2006; Griffin and Stencel, 2013). A stream of material from the F0 star to the disk was observed spectroscopically for eclipse phases 0.111 to 0.123 during the most recent eclipse (Griffin and Stencel, 2013). We did not have coverage for those phases in ESPaDOnS observations, but we do see a very confined increase in intrinsic continuum polarization in Henson (1989) $B$ band and $V$ band data from the prior (1982–1984) eclipse at phase 0.115 (Figs. 6.13 & 6.15). The trend to the PA (decreasing from phase 0.11 to 0.12) is unaffected by the additional scattered light (Figs. 6.14 & 6.16). We do not observe the phenomenon in recent broadband eclipse data, but those data are noisier.

The eclipse is largely gray (e.g. Lissauer et al., 1996) and the intrinsic continuum polarization position angle is near $90^\circ$ from mid–eclipse to 3$^{\text{rd}}$ contact through two eclipse cycles (section 6.6.3). This implies scattering from large dust grains, where $x > 1$, or grains larger than the wavelength of light. We calculated the difference in continuum polarization between $B$ band and $V$ band ($\Delta \% p_{(B-V)}$) using data from the prior (1982–1984) eclipse (Henson, 1989) and took the ratio with the propagated
uncertainty to calculate how “blue” the scattered light is through eclipse. Figure 7.1 shows that the \( \Delta \% \frac{p(B-V)}{S/N} \) for scattered light is less than 4\( \sigma \) for most of the eclipse (largely gray), except for the increase in polarization near 3\(^{\text{rd}}\) contact. The scattered light is very \( (> 5\sigma) \) blue. This suggests that small \( (x < 1) \) dust grains also contribute to the polarization at this orbital phase. We calculated an error–weighted average position angle of 89° ± 1° for epochs of polarization with \( \Delta \% \frac{p(B-V)}{S/N} \) less than 4\( \sigma \) (RJD 45536 to 45651, phases 0.093 to 0.105) and an error–weighted average position angle of 82° ± 1° for the blue scattered light (RJD 45560 to 45765, phases 0.106 to 0.116). The increased polarized light rotates the position angle to smaller angles by contributing low angles to the observed polarization, also consistent with scattering at small grains.

Line polarization arises from Rayleigh scattering at polarizable atomic transitions from gas in the disk atmosphere. The gas distribution is not symmetric; the line polarization is greater after mid–eclipse for most transitions (Tables 5.4 & 5.5). The polarized flux EW behaves differently for H\( \alpha \), H\( \beta \) and the Ca \( \text{II} \) IR triplet lines than other transitions which suggests that this gas may have a different distribution than other species. For example, the polarized flux EW for H\( \alpha \) is nearly uniform between 1\(^{\text{st}}\) and 3\(^{\text{rd}}\) contacts (Fig. 5.18).

We observe the imprint of rotation on the polarization signal consistent with models of optically thick rotating disks (Milić and Faurobert, 2014). The rotation signature is characterized by an antisymmetric Stokes \( U \) \((\%u)\), a position angle rotation across the line and a bi–lobed \( \%p \) profile.

Absorption features and line polarization probe slightly different areas of the disk. For example, we observe an increase in absorption (greater EW) in some lines.
at 1st contact (RJD 55070), but the polarized flux EW is low for most transitions at that time (e.g. Figs. 5.6, 5.11, 5.14). Trailing material contributes to absorption after 3rd contact, but we do not observe polarization (polarized flux EW is zero) in most lines (Table 5.5, RJD 55791).

The relative number of scatterers (gas and dust) along the line–of–sight is uneven during eclipse because of the thermal gradient of the disk and its asymmetries (such as trailing material). The temperature of the dust, and coupled gas, peaks after mid–eclipse because of the thermal capacity of the bulk material in the disk (Pearson and Stencel, 2015). After mid–eclipse, the number of blue–shifted scatterers is greater than the number of red–shifted scatterers in the line–of–sight because the height of gas and dust above the disk is increased due to thermal expansion in the part of the disk rotating toward the viewer. Constraints imposed by the geometry and the scattering material produce a difference of ∼ 90 days between polarization observed in the lines and in the continuum (section 5.6.2; Fig. 5.27). Figure 7.2 is a cartoon model of the system illustrating the system geometry producing the observed 3rd contact polarization.

### 7.3 F0 star considerations

I hoped to show that the F0 star is a supergiant star that has evolved off the main sequence and that mass transfer from the F0 star to the binary companion initially formed and currently sustains the disk. Many characteristics of the F0 star suggest that is not in a steady state; the irregular changes in brightness and the line profile and line polarization variability (on very short timescales!) suggest the stellar atmosphere is very dynamic; it appears more dynamic spectroscopically than typical main sequence stars whose spectra appear unchanged from observation to observation. The 2006 ESPaDOnS spectropolarimetric observation followed by ob-
servations in 2008 suggest that the outer atmosphere of the F0 star experienced large outward motion and then a gradual return to a more ‘normal’ state. Although not definitive, these observations support the view that the F0 star can experience episodic mass loss and that the mass loss could contribute material to the disk.

Additional information for two unresolved topics is presented below: the evolutionary status of the ε Aurigae system, and the source of the observed Hα emission.

7.3.1 Evolutionary status and mass loss

Hoard et al. (2010) fit the ε Aurigae F star component with a model spectrum from the Castelli & Kurucz (2004) model grid (T = 7750 K, log g = 1.0) and assumed solar metallicity abundances. They scaled the limb-darkened model spectrum to match the J–band photometric point to derive a radius of $R_F = 135 \, R_\odot$ and an angular diameter of 2.01 mas. The authors commented that the radius could only be varied by $\pm 5 \, R_\odot$, corresponding to $\pm 0.07$ mas in angular diameter, without significantly worsening the match to the J–band photometric data point. They also commented that the model angular diameter they derived is smaller than the value of $2.27 \pm 0.11$ mas measured by Stencel et al. (2008) in the K–band, but noted that their result is within 2σ. The model parameters (see Hoard et al., 2010, Table 2) lists spectral type F0 II–III (post-AGB) and not F0 Ia (supergiant) for this component of the model. The authors concluded that the mass of the F star is currently near $2.2 \, M_\odot$, while its size is that of a supergiant ($135 \, R_\odot$) due to continual mass loss via a slow expanding photosphere. Guinan (2010) described the modeled star as an unusual low-mass post–AGB supergiant and noted that typical F–type supergiants are more luminous and have masses of $10–20M_\odot$. He described a post-AGB supergiant as a bloated, short–lived and dying $1–3M_\odot$ star but noted that a progenitor
with an initial mass of 6–7$M_\odot$ could evolve from the main sequence through the AGB to a post–AGB supergiant.

If the F0 star is currently a post-AGB star, mass loss typical of AGB stars could have occurred in prior epochs to account for the mass transfer (e.g. Eggleton and Pringle, 1985). Alfvén waves, pulsation and stellar winds are possible alternative mass loss mechanisms to the typical dust–driven AGB mass loss. However, there appear to be no measurable magnetic fields present in the F0 star, even to levels of a few Gauss (Landstreet, priv. comm.). The current F0 star wind also appears to be too weak to sustain the disk (Guinan et al., 2012). For example, the spectral features of the primary indicate mass loss, $dM/dt \sim 10^{-7} \ M_\odot \ yr^{-1}$ (Castelli, 1978), which seems to be too small to result in the presence of the observed disk.

An analysis of historic records indicates that $\varepsilon$ Aurigae has been near its present visual brightness ($\pm$ 0.5 mag) since at least the time of Hipparchos ($\sim$130 B.C.) (Carroll et al. (1991), Guinan and Dewarf (2002), Johnston et al. (2012)). Large mass transfer events during the AGB phase should result in large brightness variations which have not been observed for at least several thousand years.

Sadakane et al. (2010) found no spectroscopic evidence for a post–AGB designation and concluded that observed abundances in $\varepsilon$ Aurigae are normal for high–mass supergiant stars, except for a slight over-abundances of Y, Zr, and Ba. Thermal dredge–up during the star’s evolution could produce the observed slight anomalies in heavy $s$–process elements and might indicate $s$–process nucleosynthesis has occurred in the interior of the primary star. Sadakane et al. (2010) observed the Na and Sr abundances in $\varepsilon$ Aurigae are also typical for a high–mass supergiant star.
The Na overabundance in supergiant stars is attributed to nucleosynthesis possible in massive stars.

### 7.3.2 Hα emission

Cohen (1976) noted the unexpected presence of Hα emission features in spectra of bright globular cluster and field red giant stars. The authors interpreted the emission as evidence for a circumstellar envelope of gas, produced by mass lost from the star. They observed variable Hα profiles for at least one of the sources. They suggested that a thin envelope with a low rate of mass loss (compared to stars with P Cygni profiles) could account for the blue wing emission. They also suggested that the expansion velocity was less than the escape velocity near the photosphere, but would be larger than the local escape velocity far (e.g. several hundred radii) from the star.

Emission in the wings of the Hα line in Population II giant stars can arise from within static chromospheres Dupree et al. (1984); Dupree (1993). However, these authors show that line profiles exhibiting short–wavelength peaks > long–wavelength peaks are evidence of downflow. Wavelength shifts of the core absorption are much less than the escape velocity from the stellar surface, hence line profile changes are evidence of mass flow, not mass loss. The authors used both stellar photospheres and stellar chromospheres in their models to fit the observed Hα line profiles.

Rosendhal (1973) sampled early type supergiant stars and was surprised to find Hα variability in many spectrograms of these stars. He remarked that the percentage of variables discovered (13 of 20) was truly remarkable and supported the hypothesis that all of the most luminous early-type supergiants are intrinsic variables. Several stars also showed variability in He I (λ 6678 Å) and SiII (λλ 6347Å, 6371Å).
Rosendhal also argued that Hα line profiles suggest that mass flow does not occur in a steady-state in these stars.

Barsony et al. (1986) attributed the ε Aurigae Hα emission wing variability to ongoing processes in the extended atmosphere of the supergiant. They referred to previous work on luminosity class Ia supergiants. The stars in these studies all exhibited peculiar Hα line variations, including normal and inverse P-Cygni type profiles, asymmetric absorption, and broad emission with central absorption. Barsony et al. (1986) noted that the velocity extent of the line variations seen in ε Aurigae are similar to those observed in Ia supergiants and could not rule out mass loss from the primary. They calculated the escape velocity of the primary F star, calculated for the extreme possibilities of the mass–to–radius ratio of the primary (1.1 $M_\odot$ – 40 $M_\odot$, 220 $R_\odot$ – 650 $R_\odot$), to lie in the range 18 km sec$^{-1}$ to 180 km sec$^{-1}$ and noted that the observed line-profile velocities lie toward the lower end of the allowed escape velocity range. Variable mass loss from the primary of ε Aurigae can account for a variety of the spectropolarimetry reported here as well as the current state of the disk.

7.4 Future work

There are still opportunities to learn more about the ε Aurigae system using the ESPaDOnS spectropolarimetric observations discussed here. For example, Hα is a unique tracer with contributions likely from several components in the system. The unusual Hα absorption and emission features deserve further consideration because the Hα polarization behaves differently than other lines in the spectrum. A post–eclipse HPOL Balmer jump index measurement and the ESPaDOnS Hα Stokes U profile in post–eclipse observations both hint that the intrinsic polarization may be modulated by an orbital component. It would be exciting to find and characterize
an orbital component to the polarization because this information could help resolve the distance to the system. Spectropolarimetric Stokes Q and Stokes U observations of other F supergiant stars, such as b Vel, could help inform this work. Observations spanning years on either side of the $\varepsilon$ Aurigae secondary eclipse could be especially informative if backscattering from dust grains in the disk is pronounced.

The study of evolved stars, mass loss, and mass transfer in binary systems leads to important insights into stellar structure and evolution. Energy transport in the outer stellar atmosphere is a fundamental component of mass loss. Research into stellar chromospheres or work in ultra-violet spectroscopy would be excellent follow-up projects to this thesis work because they would offer opportunities to understand higher energy physical phenomena than processes involved in visible spectra. Finally, continued observations of the bright star in $\varepsilon$ Aurigae offers the opportunity to build an understanding of complex stellar processes useful to the study of fainter objects being observed with increasingly sensitive detectors on larger telescopes.
Figure 7.1: Blueness of scattered light during eclipse. This plot illustrates the blueness of the scattered light during the prior (1982–1984) eclipse using data from Henson (1989). The difference between $B$ band and $V$ band polarization ($\Delta \% p_{(B-V)}$) divided by the propagated uncertainty results in a $S/N$ measure for each paired observation. The polarized light is largely gray ($<4\sigma$) until near 3rd contact. The increased polarized light is very blue ($>5\sigma$) for orbital phases $\phi = 0.106$ to $\phi = 0.116$. Wavelength independent (gray) absorption and polarization is attributed to large ($a > 10\mu m$) grains. The wavelength dependent polarization near 3rd contact is consistent with additional polarization arising from scattering at small ($x \ll 1$) dust grains. The dust grain size is parameterized by $x = 2\pi a/\lambda$ where $a$ is the grain radius and $\lambda$ is the wavelength of the incident radiation.
Figure 7.2: Model of polarization near 3rd contact. A cartoon model illustrating the relative position of the F0 star and the disk for epochs with an observed increase in $\%p$ near 3rd contact. The opaque dusty disk is the dark gray ellipse; the gas extends beyond the disk (light gray ellipse). An additional component of gas and dust (light gray) extends above and below the opaque dusty disk offset from disk center. The increase in polarization is first probed by the lines (observed as an increase in polarized flux EW) and then in the continuum by the broadband filters (observed as a change to intrinsic $\%p$ measured by the filter). The model proposes a scale height difference in the gas/dust distribution after mid-eclipse to account for the observed change to polarization. The disk moves to the right with time across the face of the F0 star along our line–of–sight. Here we hold the disk fixed and move the F0 star to the left with respect to the disk as in the interferometric composite image (Fig. 3.1).
Bibliography


S Bagnulo, M Landolfi, J D Landstreet, E Landi Degl’Innocenti, L Fossati, and M Sterzik. Stellar Spectropolarimetry with Retarder Waveplate and Beam Splitter


Sylvia Ekström, Cyril Georgy, Patrick Eggenberger, Georges Meynet, Nami Mowlavi, Aurélien Wyttenbach, Anahí Granada, Thibaut Decressin, Raphael Hirschi, Urs Frischknecht, Corinne Charbonnel, and André Maeder. Grids of stellar models with rotation - I. Models from 0.8 to 120 Msun at solar metallicity (Z = 0.014). *arXiv.org*, October 2011.


Robert L Kurucz. Including all the lines 11This article is part of a Special Issue on the 10th International Colloquium on Atomic Spectra and Oscillator Strengths for Astrophysical and Laboratory Plasmas. *Canadian Journal of Physics*, 89(4): 417–428, April 2011.


W J G Steemers and A M van Genderen. VBLUW photometry of two hypergiants HD 80077 (B2Ia+) and HD 74180 (F2Ia+) and of the open cluster PISMIS 11. *Astronomy and Astrophysics (ISSN 0004-6361)*, 154:308–312, January 1986.


### Appendix

#### Table A.1: Master line list

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Atom</th>
<th>Ion</th>
<th>Min&lt;sup&gt;b&lt;/sup&gt; (nm)</th>
<th>Max&lt;sup&gt;b&lt;/sup&gt; (nm)</th>
<th>Off&lt;sup&gt;c&lt;/sup&gt; (nm)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>373.690</td>
<td>Ca</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>383.540</td>
<td>H</td>
<td>1</td>
<td>383.00</td>
<td>384.00</td>
<td>0.00</td>
<td>n=2 to 9</td>
</tr>
<tr>
<td>385.560</td>
<td>Cr</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>385.590</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>385.600</td>
<td>Sc</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>385.600</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>385.610</td>
<td>Ar</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>385.640</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>388.390</td>
<td>Na</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>388.630</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>388.700</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>388.850</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>388.906</td>
<td>H</td>
<td>1</td>
<td>388.51</td>
<td>389.31</td>
<td>0.00</td>
<td>n=2 to 8</td>
</tr>
<tr>
<td>389.570</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>389.970</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>390.060</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>390.300</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>390.550</td>
<td>Si</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>391.350</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>391.840</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>392.030</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>392.290</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>392.600</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>392.790</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>393.030</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>393.366</td>
<td>Ca</td>
<td>2</td>
<td>393.07</td>
<td>393.67</td>
<td>0.00</td>
<td>g.s. Ca II K chromospheric line</td>
</tr>
<tr>
<td>393.830</td>
<td>Fe</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>394.400</td>
<td>Al</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>394.890</td>
<td>Ca</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
</tbody>
</table>

Continued on Next Page...
<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Atom</th>
<th>Ion</th>
<th>Min^b (nm)</th>
<th>Max^b (nm)</th>
<th>Off^c (nm)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>395.030</td>
<td>Y</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>395.200</td>
<td>V</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>396.150</td>
<td>Al</td>
<td>1</td>
<td>395.85</td>
<td>396.45</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>396.820</td>
<td>W</td>
<td>1</td>
<td>396.52</td>
<td>397.12</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>396.847</td>
<td>Ca</td>
<td>2</td>
<td>396.55</td>
<td>397.15</td>
<td>0.00</td>
<td>g.s. Ca II H chromospheric line</td>
</tr>
<tr>
<td>397.008</td>
<td>H</td>
<td>1</td>
<td>395.00</td>
<td>399.00</td>
<td>0.00</td>
<td>n=2 to 7</td>
</tr>
<tr>
<td>397.770</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>397.950</td>
<td>Co</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>398.200</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>398.390</td>
<td>Cr</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>398.760</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>399.110</td>
<td>Zr</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>400.210</td>
<td>Fe</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>400.530</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>401.240</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>401.430</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>402.330</td>
<td>V</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>402.340</td>
<td>V</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>402.470</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>402.830</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>402.960</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>404.580</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>404.780</td>
<td>Sc</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>404.870</td>
<td>Mn</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>405.190</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>405.300</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>405.380</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>405.620</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>405.750</td>
<td>Mg</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>406.050</td>
<td>Nd</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>406.360</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>406.600</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>406.700</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>407.170</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>407.771</td>
<td>Sr</td>
<td>2</td>
<td>407.62</td>
<td>407.90</td>
<td>0.00</td>
<td>ground state transition</td>
</tr>
<tr>
<td>408.620</td>
<td>unk</td>
<td>0</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>410.173</td>
<td>H</td>
<td>1</td>
<td>409.57</td>
<td>410.77</td>
<td>411.45</td>
<td>H delta, n=2 to 6</td>
</tr>
<tr>
<td>410.173</td>
<td>H</td>
<td>1</td>
<td>410.00</td>
<td>410.34</td>
<td>411.45</td>
<td>H delta, n=2 to 6</td>
</tr>
</tbody>
</table>

Continued on Next Page...
<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Atom</th>
<th>Ion</th>
<th>Min&lt;sup&gt;b&lt;/sup&gt; (nm)</th>
<th>Max&lt;sup&gt;b&lt;/sup&gt; (nm)</th>
<th>Off&lt;sup&gt;c&lt;/sup&gt; (nm)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>410.690</td>
<td>unk</td>
<td>0</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>411.100</td>
<td>Cr</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>412.270</td>
<td>Fe</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>412.480</td>
<td>Fe</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>412.810</td>
<td>Si</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>412.870</td>
<td>Fe</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>413.090</td>
<td>Si</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>413.210</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>414.390</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>414.610</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>414.940</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>415.100</td>
<td>Cr</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>416.150</td>
<td>Cr</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>416.360</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>417.212</td>
<td>Fe</td>
<td>1</td>
<td>417.08</td>
<td>417.34</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>417.353</td>
<td>Ti</td>
<td>2</td>
<td>417.26</td>
<td>417.48</td>
<td>0.00</td>
<td>Blend</td>
</tr>
<tr>
<td>417.760</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>417.890</td>
<td>Fe</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>418.180</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>420.230</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>420.400</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>420.540</td>
<td>Mn</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>420.710</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>420.900</td>
<td>Zr</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>421.190</td>
<td>Zr</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>421.550</td>
<td>Sr</td>
<td>2</td>
<td>421.43</td>
<td>421.67</td>
<td>426.46</td>
<td></td>
</tr>
<tr>
<td>422.550</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>422.608</td>
<td>Fe</td>
<td>2</td>
<td>422.31</td>
<td>422.91</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>422.634</td>
<td>Fe</td>
<td>1</td>
<td>422.33</td>
<td>422.93</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>422.642</td>
<td>Fe</td>
<td>1</td>
<td>422.14</td>
<td>423.14</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>422.673</td>
<td>Ca</td>
<td>1</td>
<td>422.37</td>
<td>422.97</td>
<td>426.50</td>
<td></td>
</tr>
<tr>
<td>422.730</td>
<td>Ti</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>422.740</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>423.270</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>423.290</td>
<td>Cr</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>423.300</td>
<td>W</td>
<td>1</td>
<td>423.00</td>
<td>423.60</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>423.316</td>
<td>Fe</td>
<td>2</td>
<td>423.10</td>
<td>423.50</td>
<td>426.46</td>
<td></td>
</tr>
<tr>
<td>423.320</td>
<td>Fe</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
</tbody>
</table>

Continued on Next Page...
<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Atom</th>
<th>Ion</th>
<th>Min&lt;sup&gt;b&lt;/sup&gt; (nm)</th>
<th>Max&lt;sup&gt;b&lt;/sup&gt; (nm)</th>
<th>Off&lt;sup&gt;c&lt;/sup&gt; (nm)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>423.330</td>
<td>Cr</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>424.240</td>
<td>Cr</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>424.682</td>
<td>Sc</td>
<td>2</td>
<td>424.35</td>
<td>424.90</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>424.743</td>
<td>Fe</td>
<td>1</td>
<td>424.00</td>
<td>426.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>425.080</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>425.260</td>
<td>Cr</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>425.440</td>
<td>Cr</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>425.830</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>427.480</td>
<td>Cr</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>428.970</td>
<td>Cr</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>428.973</td>
<td>Cr</td>
<td>1</td>
<td>428.67</td>
<td>429.27</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>429.020</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>429.021</td>
<td>Ti</td>
<td>2</td>
<td>428.72</td>
<td>429.32</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>429.038</td>
<td>Fe</td>
<td>1</td>
<td>428.54</td>
<td>429.54</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>430.000</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>430.190</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>430.250</td>
<td>Ca</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>430.320</td>
<td>Fe</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>430.550</td>
<td>Sr</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>430.570</td>
<td>Sc</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>430.770</td>
<td>Ca</td>
<td>1</td>
<td>431.00</td>
<td>431.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>430.790</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>430.960</td>
<td>Y</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>431.040</td>
<td>Ti</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>431.290</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>431.350</td>
<td>Cs</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>431.480</td>
<td>Ti</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>431.500</td>
<td>Ti</td>
<td>2</td>
<td>429.00</td>
<td>434.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>431.680</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>432.075</td>
<td>Sc</td>
<td>2</td>
<td>431.95</td>
<td>432.17</td>
<td>426.46</td>
<td></td>
</tr>
<tr>
<td>432.090</td>
<td>Na</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>432.095</td>
<td>Ti</td>
<td>2</td>
<td>431.95</td>
<td>432.17</td>
<td>426.46</td>
<td></td>
</tr>
<tr>
<td>432.500</td>
<td>Sc</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>432.580</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>433.070</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>433.790</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>434.047</td>
<td>H</td>
<td>1</td>
<td>433.88</td>
<td>434.28</td>
<td>426.46</td>
<td>H gamma, n=2 to 5</td>
</tr>
<tr>
<td>434.190</td>
<td>Mg</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
</tbody>
</table>

Continued on Next Page...
<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Atom</th>
<th>Ion</th>
<th>Min&lt;sup&gt;b&lt;/sup&gt; (nm)</th>
<th>Max&lt;sup&gt;b&lt;/sup&gt; (nm)</th>
<th>Off&lt;sup&gt;c&lt;/sup&gt; (nm)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>434.450</td>
<td>Cr</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>435.180</td>
<td>Cr</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>435.190</td>
<td>Mg</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>435.460</td>
<td>Sc</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>437.482</td>
<td>Ti</td>
<td>2</td>
<td>437.32</td>
<td>437.60</td>
<td>426.46</td>
<td></td>
</tr>
<tr>
<td>437.500</td>
<td>Mn</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>437.590</td>
<td>Fe</td>
<td>1</td>
<td>437.30</td>
<td>437.55</td>
<td>426.46</td>
<td>very weak line</td>
</tr>
<tr>
<td>437.980</td>
<td>Zr</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>438.360</td>
<td>Fe</td>
<td>1</td>
<td>438.20</td>
<td>438.42</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>438.430</td>
<td>Fe</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>438.538</td>
<td>Fe</td>
<td>2</td>
<td>438.47</td>
<td>438.62</td>
<td>450.95</td>
<td>blend of many</td>
</tr>
<tr>
<td>438.690</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>439.251</td>
<td>W</td>
<td>1</td>
<td>439.00</td>
<td>439.55</td>
<td>0.00</td>
<td>Multiplet member -no line</td>
</tr>
<tr>
<td>439.410</td>
<td>Ti</td>
<td>2</td>
<td>439.27</td>
<td>439.67</td>
<td>450.95</td>
<td></td>
</tr>
<tr>
<td>439.500</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>439.800</td>
<td>Y</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>440.040</td>
<td>Sc</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>440.480</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>440.770</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>440.920</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>441.110</td>
<td>TiII</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>441.360</td>
<td>Fe</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>441.510</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>441.560</td>
<td>Sc</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>441.682</td>
<td>Fe</td>
<td>2</td>
<td>441.61</td>
<td>441.87</td>
<td>450.95</td>
<td>blend</td>
</tr>
<tr>
<td>441.770</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>441.830</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>444.050</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>444.170</td>
<td>TiII</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>444.380</td>
<td>Ti</td>
<td>2</td>
<td>444.25</td>
<td>444.55</td>
<td>450.95</td>
<td></td>
</tr>
<tr>
<td>445.050</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>445.480</td>
<td>Ca</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>445.910</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>446.170</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>446.450</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>446.660</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>446.849</td>
<td>Ti</td>
<td>2</td>
<td>446.71</td>
<td>447.00</td>
<td>450.95</td>
<td></td>
</tr>
<tr>
<td>447.090</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
</tbody>
</table>

Continued on Next Page...
<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Atom</th>
<th>Ion</th>
<th>Min$^b$ (nm)</th>
<th>Max$^b$ (nm)</th>
<th>Off$^c$ (nm)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>447.290</td>
<td>Fe</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>447.600</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>448.110</td>
<td>Mg</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>448.130</td>
<td>Mg</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>448.130</td>
<td>Mg</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>448.832</td>
<td>Ti</td>
<td>2</td>
<td>448.75</td>
<td>449.00</td>
<td>450.95</td>
<td>blend with 448.919 Fe II</td>
</tr>
<tr>
<td>448.919</td>
<td>Fe</td>
<td>2</td>
<td>448.80</td>
<td>449.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>449.140</td>
<td>Fe</td>
<td>2</td>
<td>449.00</td>
<td>449.25</td>
<td>450.95</td>
<td></td>
</tr>
<tr>
<td>449.350</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>449.460</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>449.700</td>
<td>Zr</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>450.037</td>
<td>Ti</td>
<td>2</td>
<td>447.04</td>
<td>453.04</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>450.037</td>
<td>Ti</td>
<td>2</td>
<td>449.64</td>
<td>450.44</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>450.127</td>
<td>Ti</td>
<td>2</td>
<td>449.95</td>
<td>450.27</td>
<td>450.95</td>
<td></td>
</tr>
<tr>
<td>450.827</td>
<td>Ti</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>450.828</td>
<td>Fe</td>
<td>2</td>
<td>450.67</td>
<td>450.95</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>451.200</td>
<td>unk</td>
<td>0</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>451.533</td>
<td>Fe</td>
<td>2</td>
<td>451.40</td>
<td>451.65</td>
<td>456.00</td>
<td></td>
</tr>
<tr>
<td>451.840</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>452.022</td>
<td>Fe</td>
<td>2</td>
<td>451.91</td>
<td>452.14</td>
<td>456.00</td>
<td></td>
</tr>
<tr>
<td>452.263</td>
<td>Fe</td>
<td>2</td>
<td>452.12</td>
<td>452.39</td>
<td>456.00</td>
<td></td>
</tr>
<tr>
<td>452.860</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>452.950</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>453.396</td>
<td>Ti</td>
<td>2</td>
<td>453.26</td>
<td>453.52</td>
<td>456.00</td>
<td></td>
</tr>
<tr>
<td>453.420</td>
<td>Fe</td>
<td>2</td>
<td>453.20</td>
<td>453.70</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>453.430</td>
<td>Mg</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>453.860</td>
<td>V</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>453.960</td>
<td>Cr</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>454.152</td>
<td>Fe</td>
<td>2</td>
<td>454.04</td>
<td>454.26</td>
<td>456.00</td>
<td></td>
</tr>
<tr>
<td>454.400</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>454.510</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>454.950</td>
<td>Fe</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>454.960</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>454.980</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>455.230</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>455.400</td>
<td>Ba</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>455.500</td>
<td>Cr</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>455.590</td>
<td>Fe</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
</tbody>
</table>

Continued on Next Page...
<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Atom</th>
<th>Ion</th>
<th>Min&lt;sup&gt;b&lt;/sup&gt; (nm)</th>
<th>Max&lt;sup&gt;b&lt;/sup&gt; (nm)</th>
<th>Off&lt;sup&gt;c&lt;/sup&gt; (nm)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>455.864</td>
<td>Cr</td>
<td>2</td>
<td>455.72</td>
<td>455.97</td>
<td>0.00</td>
<td>also Cr II 455.87898</td>
</tr>
<tr>
<td>456.376</td>
<td>Ti</td>
<td>2</td>
<td>456.20</td>
<td>456.50</td>
<td>456.00</td>
<td></td>
</tr>
<tr>
<td>456.376</td>
<td>Ti</td>
<td>2</td>
<td>455.38</td>
<td>457.38</td>
<td></td>
<td></td>
</tr>
<tr>
<td>456.380</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>No</td>
</tr>
<tr>
<td>456.580</td>
<td>Ce</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>456.830</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>457.197</td>
<td>Ti</td>
<td>2</td>
<td>457.05</td>
<td>457.32</td>
<td>455.97</td>
<td></td>
</tr>
<tr>
<td>457.633</td>
<td>Fe</td>
<td>2</td>
<td>457.50</td>
<td>457.76</td>
<td>455.97</td>
<td></td>
</tr>
<tr>
<td>458.280</td>
<td>Fe</td>
<td>2</td>
<td>455.00</td>
<td>459.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>458.380</td>
<td>Fe</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>458.820</td>
<td>Cr</td>
<td>2</td>
<td>458.67</td>
<td>458.90</td>
<td>462.13</td>
<td></td>
</tr>
<tr>
<td>458.820</td>
<td>Cr</td>
<td>2</td>
<td>458.00</td>
<td>459.20</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>458.990</td>
<td>Cr</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>459.000</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>459.205</td>
<td>Cr</td>
<td>2</td>
<td>459.10</td>
<td>459.30</td>
<td>458.50</td>
<td></td>
</tr>
<tr>
<td>459.353</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>459.393</td>
<td>Ce</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>459.610</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>461.662</td>
<td>Cr</td>
<td>2</td>
<td>461.50</td>
<td>462.20</td>
<td>464.00</td>
<td></td>
</tr>
<tr>
<td>461.876</td>
<td>Fe</td>
<td>1</td>
<td>461.73</td>
<td>461.98</td>
<td>0.00</td>
<td>M101</td>
</tr>
<tr>
<td>461.881</td>
<td>Cr</td>
<td>2</td>
<td>461.75</td>
<td>461.96</td>
<td>464.00</td>
<td>blend with Fe I?</td>
</tr>
<tr>
<td>462.051</td>
<td>Fe</td>
<td>2</td>
<td>461.96</td>
<td>462.15</td>
<td>464.00</td>
<td>Yes</td>
</tr>
<tr>
<td>462.160</td>
<td>C</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>462.929</td>
<td>Ti</td>
<td>2</td>
<td>462.63</td>
<td>463.23</td>
<td>464.00</td>
<td>blend with Fe II</td>
</tr>
<tr>
<td>462.929</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>464.00</td>
<td>blend with Fe II</td>
</tr>
<tr>
<td>462.933</td>
<td>Fe</td>
<td>2</td>
<td>462.78</td>
<td>463.08</td>
<td>464.00</td>
<td></td>
</tr>
<tr>
<td>462.933</td>
<td>Fe</td>
<td>2</td>
<td>462.00</td>
<td>464.50</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>463.407</td>
<td>Cr</td>
<td>2</td>
<td>463.28</td>
<td>463.54</td>
<td>464.00</td>
<td></td>
</tr>
<tr>
<td>463.530</td>
<td>Fe</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>464.743</td>
<td>Fe</td>
<td>1</td>
<td>464.59</td>
<td>464.89</td>
<td></td>
<td>M101- no line</td>
</tr>
<tr>
<td>464.870</td>
<td>Ni</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>464.900</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>465.698</td>
<td>Fe</td>
<td>2</td>
<td>465.60</td>
<td>465.83</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>465.720</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>466.370</td>
<td>Fe</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>466.680</td>
<td>Fe</td>
<td>2</td>
<td>463.00</td>
<td>467.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>467.041</td>
<td>Sc</td>
<td>2</td>
<td>466.89</td>
<td>467.19</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>468.230</td>
<td>Y</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
</tbody>
</table>

Continued on Next Page...
<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Atom</th>
<th>Ion</th>
<th>Min(^b) (nm)</th>
<th>Max(^b) (nm)</th>
<th>Off(^c) (nm)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>470.300</td>
<td>Mg</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>470.380</td>
<td>Ni</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>470.870</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>473.144</td>
<td>Fe</td>
<td>2</td>
<td>473.00</td>
<td>473.28</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>476.290</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>477.170</td>
<td>C</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>477.998</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>479.850</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>480.509</td>
<td>Ti</td>
<td>2</td>
<td>480.35</td>
<td>480.65</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>480.542</td>
<td>Ti</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>481.240</td>
<td>Cr</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>482.413</td>
<td>Cr</td>
<td>2</td>
<td>482.10</td>
<td>482.75</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>482.417</td>
<td>Fe</td>
<td>1</td>
<td>482.10</td>
<td>482.75</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>483.620</td>
<td>Cr</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>484.825</td>
<td>Cr</td>
<td>2</td>
<td>484.69</td>
<td>484.95</td>
<td>487.85</td>
<td></td>
</tr>
<tr>
<td>485.510</td>
<td>Sr</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>486.037</td>
<td>Cr</td>
<td>1</td>
<td>485.90</td>
<td>486.30</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>486.068</td>
<td>Fe</td>
<td>2</td>
<td>485.90</td>
<td>486.30</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>486.098</td>
<td>Fe</td>
<td>1</td>
<td>485.90</td>
<td>486.30</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>486.135</td>
<td>H</td>
<td>1</td>
<td>485.90</td>
<td>486.30</td>
<td>487.85</td>
<td>n=2 to 4, H beta</td>
</tr>
<tr>
<td>486.430</td>
<td>Cr</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>486.560</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>487.400</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>487.649</td>
<td>Cr</td>
<td>2</td>
<td>487.52</td>
<td>487.75</td>
<td>487.85</td>
<td></td>
</tr>
<tr>
<td>488.370</td>
<td>Y</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>488.460</td>
<td>Cr</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>489.075</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>M84</td>
</tr>
<tr>
<td>489.149</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>M84</td>
</tr>
<tr>
<td>489.380</td>
<td>Fe</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>490.010</td>
<td>Y</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>491.120</td>
<td>Ti</td>
<td>2</td>
<td>490.99</td>
<td>491.25</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>491.899</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>M84</td>
</tr>
<tr>
<td>492.050</td>
<td>Fe</td>
<td>1</td>
<td>491.95</td>
<td>492.15</td>
<td>0.00</td>
<td>M84</td>
</tr>
<tr>
<td>492.392</td>
<td>Fe</td>
<td>2</td>
<td>492.20</td>
<td>492.65</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>493.408</td>
<td>Ba</td>
<td>2</td>
<td>493.20</td>
<td>493.60</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>495.730</td>
<td>Fe</td>
<td>1</td>
<td>495.50</td>
<td>496.02</td>
<td>0.00</td>
<td>M84</td>
</tr>
<tr>
<td>495.760</td>
<td>Fe</td>
<td>1</td>
<td>495.50</td>
<td>496.02</td>
<td>0.00</td>
<td>M84</td>
</tr>
<tr>
<td>499.330</td>
<td>Fe</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
</tbody>
</table>

Continued on Next Page...
<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Atom</th>
<th>Ion</th>
<th>Min$^b$ (nm)</th>
<th>Max$^b$ (nm)</th>
<th>Off$^c$ (nm)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>501.370</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>501.733</td>
<td>Cr</td>
<td>1</td>
<td>501.43</td>
<td>502.03</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>501.749</td>
<td>Sc</td>
<td>1</td>
<td>501.45</td>
<td>502.05</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>501.816</td>
<td>Cr</td>
<td>1</td>
<td>501.52</td>
<td>502.12</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>501.844</td>
<td>Fe</td>
<td>2</td>
<td>501.60</td>
<td>502.10</td>
<td>0.00</td>
<td>Blend</td>
</tr>
<tr>
<td>501.920</td>
<td>Cr</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>503.078</td>
<td>Fe</td>
<td>1</td>
<td>502.95</td>
<td>503.21</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>503.100</td>
<td>Sc</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>503.100</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>504.100</td>
<td>Si</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>505.600</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>506.880</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>507.270</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>509.720</td>
<td>K</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>510.100</td>
<td>Fe</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>510.940</td>
<td>Ti</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>510.970</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>510.980</td>
<td>Tc</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>511.030</td>
<td>O</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>511.040</td>
<td>Fe</td>
<td>1</td>
<td>510.00</td>
<td>512.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>511.190</td>
<td>O</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>511.250</td>
<td>Cr</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>512.040</td>
<td>Ti</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>512.320</td>
<td>Y</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>512.916</td>
<td>Ti</td>
<td>2</td>
<td>512.80</td>
<td>513.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>513.270</td>
<td>Fe</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>513.680</td>
<td>Fe</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>513.920</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>514.030</td>
<td>O</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>514.190</td>
<td>O</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>514.610</td>
<td>Fe</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>515.080</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>515.410</td>
<td>Ti</td>
<td>2</td>
<td>515.20</td>
<td>515.60</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>515.990</td>
<td>Ba</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>516.732</td>
<td>Mg</td>
<td>1</td>
<td>516.60</td>
<td>516.78</td>
<td>515.60</td>
<td></td>
</tr>
<tr>
<td>516.749</td>
<td></td>
<td></td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>516.890</td>
<td>Fe</td>
<td>1</td>
<td>516.77</td>
<td>517.09</td>
<td>515.60</td>
<td></td>
</tr>
<tr>
<td>516.890</td>
<td>Fe</td>
<td>1</td>
<td>516.39</td>
<td>517.19</td>
<td>0.00</td>
<td></td>
</tr>
</tbody>
</table>

Continued on Next Page...
<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Atom</th>
<th>Ion</th>
<th>Min(^b) (nm)</th>
<th>Max(^b) (nm)</th>
<th>Off(^c) (nm)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>516.903</td>
<td>Fe</td>
<td>2</td>
<td>516.77</td>
<td>517.05</td>
<td>515.60</td>
<td></td>
</tr>
<tr>
<td>516.930</td>
<td>Fe</td>
<td>1</td>
<td>516.77</td>
<td>517.05</td>
<td>515.60</td>
<td>blend Fe II 516.903?</td>
</tr>
<tr>
<td>517.268</td>
<td>Mg</td>
<td>1</td>
<td>517.05</td>
<td>517.45</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>518.360</td>
<td>Mg</td>
<td>1</td>
<td>518.20</td>
<td>518.46</td>
<td>517.60</td>
<td></td>
</tr>
<tr>
<td>518.360</td>
<td>Mg</td>
<td>1</td>
<td>518.20</td>
<td>518.88</td>
<td>517.60</td>
<td></td>
</tr>
<tr>
<td>518.950</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>518.960</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>518.870</td>
<td>Ti</td>
<td>2</td>
<td>518.74</td>
<td>519.00</td>
<td>517.60</td>
<td></td>
</tr>
<tr>
<td>519.757</td>
<td>Fe</td>
<td>2</td>
<td>519.60</td>
<td>519.90</td>
<td>517.60</td>
<td></td>
</tr>
<tr>
<td>520.450</td>
<td>Cr</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>520.450</td>
<td>Cr</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>520.600</td>
<td>Cr</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>520.600</td>
<td>Cr</td>
<td>1</td>
<td>520.00</td>
<td>521.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>520.840</td>
<td>Cr</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>520.840</td>
<td>Cr</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>522.654</td>
<td>Ti</td>
<td>2</td>
<td>522.52</td>
<td>522.80</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>522.719</td>
<td>Fe</td>
<td>1</td>
<td>522.59</td>
<td>522.85</td>
<td>524.10</td>
<td></td>
</tr>
<tr>
<td>523.290</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>523.462</td>
<td>Fe</td>
<td>2</td>
<td>523.33</td>
<td>523.59</td>
<td>524.10</td>
<td></td>
</tr>
<tr>
<td>523.736</td>
<td>Cr</td>
<td>2</td>
<td>523.57</td>
<td>523.88</td>
<td>524.10</td>
<td></td>
</tr>
<tr>
<td>523.980</td>
<td>Sc</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>524.960</td>
<td>Nd</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>525.040</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>525.490</td>
<td>Cr</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>525.496</td>
<td>Fe</td>
<td>1</td>
<td>527.35</td>
<td>527.85</td>
<td>528.50</td>
<td>blend?</td>
</tr>
<tr>
<td>525.500</td>
<td>Fe</td>
<td>1</td>
<td>525.40</td>
<td>525.60</td>
<td>525.75</td>
<td></td>
</tr>
<tr>
<td>525.500</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>525.570</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>525.690</td>
<td>Fe</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>526.220</td>
<td>Ca</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>526.480</td>
<td>Fe</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>526.650</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>526.950</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>527.500</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>527.527</td>
<td>Cr</td>
<td>1</td>
<td>527.35</td>
<td>527.85</td>
<td>528.50</td>
<td>blend?</td>
</tr>
<tr>
<td>527.600</td>
<td>Fe</td>
<td>2</td>
<td>527.35</td>
<td>527.85</td>
<td>528.50</td>
<td></td>
</tr>
<tr>
<td>527.990</td>
<td>Cr</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>528.440</td>
<td>Fe</td>
<td>1</td>
<td>528.25</td>
<td>528.55</td>
<td>528.50</td>
<td></td>
</tr>
</tbody>
</table>

Continued on Next Page...
<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Atom</th>
<th>Ion</th>
<th>Min&lt;sup&gt;b&lt;/sup&gt; (nm)</th>
<th>Max&lt;sup&gt;b&lt;/sup&gt; (nm)</th>
<th>Off&lt;sup&gt;c&lt;/sup&gt; (nm)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>530.590</td>
<td>Cr</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>530.840</td>
<td>Cr</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>531.070</td>
<td>Cr</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>531.360</td>
<td>Cr</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>531.580</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>531.600</td>
<td>Fe</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>531.620</td>
<td>Fe</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>531.660</td>
<td>Fe</td>
<td>2</td>
<td>531.20</td>
<td>532.10</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>531.661</td>
<td>Fe</td>
<td>2</td>
<td>531.50</td>
<td>531.80</td>
<td>531.90</td>
<td></td>
</tr>
<tr>
<td>531.678</td>
<td>Fe</td>
<td>2</td>
<td>531.45</td>
<td>531.90</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>531.680</td>
<td>Fe</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>532.420</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>532.560</td>
<td>Fe</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>532.800</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>533.490</td>
<td>Cr</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>533.680</td>
<td>Ti</td>
<td>2</td>
<td>533.55</td>
<td>533.85</td>
<td>534.15</td>
<td></td>
</tr>
<tr>
<td>534.700</td>
<td>Ca</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>536.275</td>
<td>Fe</td>
<td>2</td>
<td>536.15</td>
<td>536.40</td>
<td>534.15</td>
<td></td>
</tr>
<tr>
<td>537.150</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>538.102</td>
<td>Ti</td>
<td>2</td>
<td>537.96</td>
<td>538.24</td>
<td>534.15</td>
<td></td>
</tr>
<tr>
<td>538.340</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>539.710</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>540.420</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>540.580</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>540.760</td>
<td>Cr</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>541.410</td>
<td>Fe</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>541.520</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>541.877</td>
<td>Ti</td>
<td>2</td>
<td>541.74</td>
<td>542.02</td>
<td>544.10</td>
<td></td>
</tr>
<tr>
<td>542.530</td>
<td>Fe</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>542.780</td>
<td>Fe</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>542.970</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>543.290</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>543.450</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>544.690</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>545.560</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>549.740</td>
<td>Y</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>550.210</td>
<td>Cr</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
</tbody>
</table>

Continued on Next Page...
<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Atom</th>
<th>Ion</th>
<th>Min(^b) (nm)</th>
<th>Max(^b) (nm)</th>
<th>Off(^c) (nm)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>550.860</td>
<td>Cr</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>551.080</td>
<td>Fe</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>551.300</td>
<td>Ca</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>552.679</td>
<td>Sc</td>
<td>2</td>
<td>252.55</td>
<td>552.80</td>
<td>553.00</td>
<td></td>
</tr>
<tr>
<td>552.760</td>
<td>Ti</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>553.484</td>
<td>Fe</td>
<td>1</td>
<td>553.34</td>
<td>553.62</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>557.280</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>558.680</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>561.560</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>562.450</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>562.750</td>
<td>Fe</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>564.100</td>
<td>Sc</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>565.900</td>
<td>Sc</td>
<td>2</td>
<td>565.65</td>
<td>565.93</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>566.250</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>566.710</td>
<td>Sc</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>566.900</td>
<td>Sc</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>568.420</td>
<td>Sc</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>568.820</td>
<td>Na</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>578.060</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>579.700</td>
<td>DIB</td>
<td>0</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>579.740</td>
<td>Ti</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>581.900</td>
<td>Sr</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>585.370</td>
<td>Ba</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>588.889</td>
<td>Ti</td>
<td>2</td>
<td>588.75</td>
<td>589.03</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>589.592</td>
<td>Na</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>595.670</td>
<td>Ca</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>595.670</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>597.890</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>599.190</td>
<td>Co</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>608.410</td>
<td>Fe</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>611.330</td>
<td>Fe</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>614.170</td>
<td>Ba</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>614.780</td>
<td>Fe</td>
<td>2</td>
<td>614.63</td>
<td>614.85</td>
<td>0.00</td>
<td>weak</td>
</tr>
<tr>
<td>614.923</td>
<td>Fe</td>
<td>2</td>
<td>614.85</td>
<td>615.05</td>
<td>0.00</td>
<td>weak</td>
</tr>
<tr>
<td>615.820</td>
<td>O</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>616.210</td>
<td>Ca</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>623.838</td>
<td>Fe</td>
<td>2</td>
<td>623.69</td>
<td>623.99</td>
<td>624.10</td>
<td></td>
</tr>
</tbody>
</table>

Continued on Next Page...
<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Atom</th>
<th>Ion</th>
<th>Min\textsuperscript{b} (nm)</th>
<th>Max\textsuperscript{b} (nm)</th>
<th>Off\textsuperscript{c} (nm)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>624.756</td>
<td>Fe</td>
<td>2</td>
<td>624.61</td>
<td>624.91</td>
<td>624.10</td>
<td></td>
</tr>
<tr>
<td>631.800</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>634.710</td>
<td>Si</td>
<td>2</td>
<td>634.40</td>
<td>635.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>637.140</td>
<td>Si</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>637.150</td>
<td>Ti</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>637.900</td>
<td>DIB</td>
<td>0</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>638.373</td>
<td>Fe</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>Multiplet (40)</td>
</tr>
<tr>
<td>638.546</td>
<td>Fe</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>Multiplet (40)</td>
</tr>
<tr>
<td>641.690</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>641.693</td>
<td>Fe</td>
<td>2</td>
<td>641.54</td>
<td>641.84</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>643.268</td>
<td>Fe</td>
<td>2</td>
<td>643.12</td>
<td>643.42</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>645.638</td>
<td>Fe</td>
<td>2</td>
<td>645.45</td>
<td>645.80</td>
<td>646.40</td>
<td></td>
</tr>
<tr>
<td>649.690</td>
<td>Ba</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>650.000</td>
<td>All</td>
<td>1</td>
<td>646.00</td>
<td>670.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>651.608</td>
<td>Fe</td>
<td>2</td>
<td>651.46</td>
<td>651.76</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>655.960</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>656.010</td>
<td>H</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>656.220</td>
<td>Fe</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>Multiplet (40)</td>
</tr>
<tr>
<td>656.280</td>
<td>H</td>
<td>1</td>
<td>655.84</td>
<td>656.71</td>
<td>0.00</td>
<td>H alpha, n=2 to 3</td>
</tr>
<tr>
<td>656.415</td>
<td>Cr</td>
<td>1</td>
<td>655.84</td>
<td>656.71</td>
<td>0.00</td>
<td>Blended in H\textalpha{}</td>
</tr>
<tr>
<td>658.671</td>
<td>Fe</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>Multiplet (40)</td>
</tr>
<tr>
<td>658.760</td>
<td>C</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>660.460</td>
<td>Sc</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>661.300</td>
<td>DIB</td>
<td>0</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>661.360</td>
<td>Ti</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>661.380</td>
<td>Y</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>682.800</td>
<td>Ti</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>726.540</td>
<td>Ti</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>726.630</td>
<td>Ti</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>742.360</td>
<td>N</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>742.600</td>
<td>Si</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>746.240</td>
<td>Cr</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>746.830</td>
<td>N</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>766.490</td>
<td>K</td>
<td>1</td>
<td>766.25</td>
<td>766.80</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>769.896</td>
<td>K</td>
<td>1</td>
<td>769.79</td>
<td>770.00</td>
<td>700.60</td>
<td></td>
</tr>
<tr>
<td>771.100</td>
<td>Fe</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>771.170</td>
<td>Fe</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>773.104</td>
<td>Fe</td>
<td>2</td>
<td>772.80</td>
<td>773.40</td>
<td>0.00</td>
<td></td>
</tr>
</tbody>
</table>

Continued on Next Page...
<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Atom</th>
<th>Ion</th>
<th>Min$^b$ (nm)</th>
<th>Max$^b$ (nm)</th>
<th>Off$^c$ (nm)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>777.194</td>
<td>O</td>
<td>1</td>
<td>777.00</td>
<td>778.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>777.417</td>
<td>O</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>777.430</td>
<td>O</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>No</td>
</tr>
<tr>
<td>777.539</td>
<td>O</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>821.630</td>
<td>N</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>824.880</td>
<td>Ca</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>828.642</td>
<td>Pa30</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>829.230</td>
<td>Pa29</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>829.883</td>
<td>Pa28</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>832.342</td>
<td>Pa25</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>833.378</td>
<td>Pa24</td>
<td>1</td>
<td>833.00</td>
<td>834.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>833.439</td>
<td>Ti</td>
<td>1</td>
<td>833.00</td>
<td>834.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>833.504</td>
<td>Sc</td>
<td>2</td>
<td>833.00</td>
<td>834.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>834.554</td>
<td>Pa23</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>835.900</td>
<td>Pa22</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>837.448</td>
<td>Pa21</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>839.240</td>
<td>Pa20</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>841.332</td>
<td>Pa19</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>844.630</td>
<td>O</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>844.640</td>
<td>O</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>844.640</td>
<td>O</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>844.680</td>
<td>O</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>846.726</td>
<td>H</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>Pa17 n=3 to 17</td>
</tr>
<tr>
<td>849.802</td>
<td>Ca</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>850.249</td>
<td>H</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>Pa16 n=3 to 16</td>
</tr>
<tr>
<td>854.209</td>
<td>Ca</td>
<td>2</td>
<td>854.00</td>
<td>855.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>854.538</td>
<td>H</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>Pa15 n=3 to 15</td>
</tr>
<tr>
<td>859.400</td>
<td>??</td>
<td>0</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>859.839</td>
<td>H</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>Pa14 n=3 to 14</td>
</tr>
<tr>
<td>862.930</td>
<td>N</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>862.930</td>
<td>N</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>866.214</td>
<td>Ca</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>866.230</td>
<td>Ca</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>866.502</td>
<td>H</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>Pa13 n=3 to 13</td>
</tr>
<tr>
<td>868.020</td>
<td>Si</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>870.330</td>
<td>N</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>871.170</td>
<td>N</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
</tbody>
</table>

Continued on Next Page...
Table A.1 – Continued

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Atom</th>
<th>Ion</th>
<th>Min&lt;sup&gt;b&lt;/sup&gt; (nm)</th>
<th>Max&lt;sup&gt;b&lt;/sup&gt; (nm)</th>
<th>Off&lt;sup&gt;c&lt;/sup&gt; (nm)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>871.880</td>
<td>N</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>872.890</td>
<td>N</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>874.740</td>
<td>N</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>875.046</td>
<td>H</td>
<td>1</td>
<td>874.50</td>
<td>875.50</td>
<td>0.00</td>
<td>Pa12 n=3 to 12</td>
</tr>
<tr>
<td>880.680</td>
<td>Mg</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>886.289</td>
<td>H</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>Pa11 n=3 to 11</td>
</tr>
<tr>
<td>901.530</td>
<td>H</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>Pa10 n=3 to 10</td>
</tr>
<tr>
<td>922.970</td>
<td>H</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>Pa9 n=3 to 9</td>
</tr>
<tr>
<td>954.620</td>
<td>H</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>Pa8 n=3 to 8</td>
</tr>
</tbody>
</table>

<sup>a</sup>Master line list compiled from Hack (1959); Strassmeier et al. (2014).

<sup>b</sup>Beginning and ending wavelengths used to integrate equivalent width (EW) and polarized flux EW.

<sup>c</sup>The width of the wavelength range was the same as the range across the line determined by the minimum and maximum wavelengths. Zero indicates that the ending wavelength was used as the beginning offline wavelength.