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Mass Loss History of Evolved Stars

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MASS LOSS HISTORY OF EVOLVED STARS

A THESIS
PRESENTED TO
THE FACULTY OF NATURAL SCIENCES AND MATHEMATICS
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BY
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ADVISOR: DR. TOSHIYA UETA
Abstract

We provide high-resolution maps of the circumstellar dust shells of several dozen Asymptotic Giant Branch (AGB) stars using data from the Spitzer space telescope Multiband Imaging Photometer (MIPS) imaged at 70μm. AGB stars are the major contributors of chemical elements such as carbon, oxygen and silicon, which are essential to the existence of life in the universe, through mass loss processes that take place at the surface of the star. We probe the spatial distribution of cold (∼40 K) dust grains in order to trace the history of mass loss from the observed radial density variation in these shells. Our images illustrate that different morphologies may evolve because AGB stars can already interact with the interstellar medium (ISM) that surrounds them even at these early stages of the AGB mass loss history. Relative motion of the star as well as the ISM with respect to the local environment may be of particular importance for shell structure evolution.
Acknowledgements

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Chapter 1

Introduction

1.1 Overview

Low to intermediate mass stars (0.8M⊙ - 8 M⊙) evolve off the main sequence to become asymptotic giant branch (AGB) stars [1]. During the AGB phase, these stars lose mass which forms a shell of gas and dust surrounding the star. The shell contains new elements formed during nucleosynthesis as well as elements from the original material that formed the star. The circumstellar material mixes into the interstellar medium (ISM) to become part of the next cycle of star formation. The circumstellar shell retains the fossil record of the mass loss processes under which it formed. Changes to mass loss are imprinted in the shell as density variations. We may investigate the nature of mass loss in the AGB by observing the density structure of the circumstellar shell.

Mass loss in the Early AGB (EAGB) is thought to be spherically symmetric [2]. Studies of proto-planetary nebulae (PPNe), post-AGB objects, have shown that axisymmetric structures commonly occur (e.g.[3, 4, 5]). Planetary nebulae (PNe) are the final stage in the evolution of mass loss and they exhibit intricately complex structures. Asymmetries present in circumstellar shells such as those in PPNe and
PNe suggest that some change to the nature of mass loss must happen before the late AGB in order for asymmetries to form.

Observing far-infrared emission of cold dust in the circumstellar shell is an effective way to probe the mass loss history of the shell. The interstellar radiation field (ISRF) heats dust in the outer region of the shell to $\sim$20K - 40K, but gas molecules in this region may be photo-dissociated; therefore, dust is a better tracer of mass loss history at the outer regions of the shell. In addition, the outer regions of the shell reach farther back into the history of mass loss. We form a more complete picture of early mass loss history by observing at wavelengths (e.g. 70$\mu$m) that capture this cold dust emission.

Recent observations have shown that bow shock structures may form at the interface between the circumstellar shell and the ISM. Ueta et al. have shown that even weak shocks arising from the relative flow between the ISM and the outwardly moving shell may heat dust grains in the outer regions of the shell [6]. Cold dust emission unveils the region where the shell and the ISM interact and allows us to investigate further the nature of these interactions.

This thesis characterizes the AGB mass loss variation in circumstellar dust shells for several dozen AGB stars, through groupings that highlight the underlying processes contributing to the morphology of each shell, using Spitzer Space Telescope Multiband Imaging Photometer (MIPS) 70$\mu$m observations. The thesis presents measurement of dust mass for the extended portion of the shell, provides estimates of dynamical age, and also quantifies the azimuthally-averaged density variation in the shell.

The remaining portions of this thesis are arranged as follows: the introduction gives an overview of stellar evolution, describes characteristics of the evolved stars in the study, introduces theories of dust formation and stellar winds, and provides a brief history of far-IR space-based telescopes to illustrate the importance of these
far-IR observations. Chapter 2 presents the methodology used in preparing and analyzing the data, Chapter 3 includes the results of observations, and conclusions are presented in Chapter 4.

1.2 Post-main sequence stars

Stars whose initial main-sequence mass is in the low to intermediate range (0.8 $M_\odot$ - 8 $M_\odot$) go through an evolutionary phase known as the asymptotic giant branch [7, 1]. Stars more massive than 0.8 $M_\odot$ can evolve from core hydrogen burning (main sequence) to core helium burning and beyond. Stars more massive than 8 $M_\odot$ do not enter the AGB phase and eventually end catastrophically as supernovae. When hydrogen is exhausted in the core of low- to intermediate- mass stars they first progress to burning hydrogen in a shell outside the core and then to burning helium in the core. Eventually AGB stars evolve asymptotically along the red giant branch on the Hertzsprung-Russell (HR) diagram (see Fig. 1.1). During the early AGB (EAGB) a low- to intermediate- mass star burns helium in a shell beneath a convective envelope. The core contracts but the envelope expands and cools. Over time, the core becomes increasingly composed of carbon and oxygen. The luminosity increases ($\sim$6,000$L_\odot$) but $T_{\text{eff}}$, the effective temperature (near the surface of the star) is low ($\leq$3,000K). As the helium burning shell moves outward through the envelope it eventually encounters hydrogen which can re-ignite. The star evolves to a phase, called the thermally-pulsing AGB (TPAGB), where hydrogen and helium burn alternately in thin shells.

Thermonuclear runaway events may occur during the TPAGB [7]. The ‘thermal pulse’ events repeat every 10,000 to 100,000 years depending upon the mass of the star. Thermal pulses create convective zones that reach deep into the star and help to lift material to the stellar surface; this process is called “dredge-up” [8]. Dredge up in the TPAGB is the third dredge-up because this process may occur during two
Figure 1.1: Hertzsprung-Russell diagram of a complete $2M_\odot$ evolution track for a star of similar metallicity as the Sun. The track describes the stellar evolution from the main sequence to the white dwarf phase. In the cooler section of the post-AGB phase, wiggles in the track are caused by numerical convergence difficulties in the model. The blue track shows an alternate evolution triggered by a late thermal pulse. The red and green stars mark the position of known central stars of planetary nebulae (PG 1159-035 and NGC 6853). The number labels for each evolutionary phase indicate the log of the approximate duration for a $2M_\odot$ case. Larger or smaller mass cases would have smaller or larger evolutionary timescales, respectively. Herwig [1]

earlier phases of the stellar lifetime. Carbon and isotopes of heavy elements that have been synthesized in the helium burning shell are brought up into the hydrogen-rich envelope and alter the chemical composition of the star [9]. The atmospheric abundance ratio (number fraction[1]) of carbon to oxygen, C/O, may be less than 1 for an oxygen-rich star, about 1 for an S star, or greater than 1 for a carbon star. A star of spectral type S (an S star) has a spectrum similar to an oxygen-rich spectral type M star, but the dust emission peaks at $\sim$10.5µm - 10.8µm and the spectrum includes characteristic zirconium oxide (ZrO) bands [10].
The outer envelope of an AGB star becomes thermally unstable and begins to pulsate on a time scale of the order of 100 to 700 days, considered Long Period Variable (LPV) [11]. LPV stars are classified as Mira-like (M), which exhibit regular variability, Semi-regular (SRa and SRb), or irregular (L) based on their spectra (See the General Catalogue of Variable Stars [12]). The pulsation of the star helps form a stellar wind that drives gas and dust away from the star. Atmospheric shock waves form which lift gas above the surface of the star where it is cool enough for the gas to condense and form dust.

The regions surrounding an AGB star are depicted in Figure 1.2 (not to scale). The star has a degenerate C/O core with shells of hydrogen and helium that alternately burn. A convective envelope (yellow arrows) helps to lift material from the core to the outer regions of the star. The outer edge of the star is indicated by orange arrows. Beyond the edge of the star is the stellar atmosphere, which is a region cool enough for molecular gas species to form. The dominant gas species in this region are molecular hydrogen (H$_2$) and carbon monoxide (CO). Surrounding the stellar atmosphere is a region containing the stellar wind. Here particulates condense out of the gas. Dominant particulate (dust) species are silicates in oxygen-rich stars and amorphous carbon in carbon-rich stars. The wind reaches terminal velocity in the region marked as the circumstellar envelope. In this region dust and gas expand into the interstellar medium (ISM). The circumstellar dust shell begins at $\sim 10^{14}$ cm, where the temperature is cool enough for dust to condense, and extends to the outer edge of the shell at $\sim 10^{18}$ cm (see section 1.3). For a comparison of scale, the planet Neptune orbits the Sun at about 30 astronomical units (AU) which corresponds to approximately $4 \times 10^{14}$ cm. The region where the dust and gas lost by the star mix with the ISM is shaded blue in the diagram.

The mass loss rate effectively determines the lifespan of an AGB star [11]. The mass loss rate varies from $10^{-7}$ M$_\odot$ yr$^{-1}$ to $10^{-4}$ M$_\odot$ yr$^{-1}$ [13]. Toward the end
of the AGB, the mass loss rate increases dramatically and a ‘superwind’ forms [14]. Observations of AGB stars and post-AGB stars have supported the superwind hypothesis (e.g. [15]) and it has been computationally shown to arise on the AGB (e.g. [11]). The mass of the envelope decreases as mass loss removes material from the surface of the star.

Over time almost all the matter surrounding an AGB star will disperse into space. The AGB phase ends when mass loss virtually ceases and the circumstellar shell physically detaches and begins to drift away from the star. The star enters the post-AGB phase. It briefly becomes a proto-planetary nebula (PPN) and then a planetary nebula (PN). The planetary nebula phase is marked by glowing gas ionized by a hot central star. The central star emits enough ultraviolet (UV) photons to photoionize the circumstellar material when the surface temperature reaches about $3 \times 10^4 \text{K}$. High resolution images of planetary nebulae reveal complex extended structures that deviate significantly from spherical symmetry, but generally may be considered axisymmetric (e.g. [16, 17]). The post-AGB phase is short ($\sim 10^3 \text{yr}$) and the duration depends strongly on the mass of the central star [8].

1.3 Dust formation

The species of dust formed in the circumstellar shell depend upon the relative abundances of carbon and oxygen. Silicates are the dominant species for stars with $C/O < 1$. Gail & Sedlmayr found the most stable condensate formed from the elements O, Si, Mg, and Fe (each with sufficient abundance in O-rich stars) is the magnesium-iron silicate $\text{Mg}_2\text{Fe}_{2(1-x)}\text{SiO}_4$ with $x \in [0, 1]$ (the mixed compound with $0 < x < 1$ is called olivine) [18]. Amorphous carbon is the dominant species for stars with $C/O > 1$. The grains are thought to have a range of sizes, for example: Sargent et al. modeled spectral energy distributions (SEDs) and spectra of O-rich stars in the Large Magellanic Cloud (LMC) using the radiative transfer code 2Dust.
Figure 1.2: A model of the circumstellar regions surrounding an AGB star (not to scale). The star has a degenerate C/O core with alternating He- and H- burning shells. A convective envelope helps to lift material from the core to the outer regions of the star. The stellar atmosphere is a region cool enough for molecular gas species to form. The dominant species in this region are H$_2$ and CO. Surrounding the stellar atmosphere is a region containing the stellar wind. Here particulates condense out of the gas. Dominant particulate (dust) species are silicates in oxygen-rich stars and amorphous carbon in carbon-rich stars. The circumstellar envelope expands into the interstellar medium (ISM). Adapted from Habing [2]

[19] and found that a distribution of grain sizes between 0.01 µm and 0.1 µm ($a_{\text{min}}$ and $a_0$) provided good fits of models to observed data [20]. Heras & Hony found $a_{\text{min}} = 0.005$ µm and $a_0 = 0.2$ µm provided good fits to spectra for O-rich stars with optically thin dust shells [21]. Seed nuclei for grain growth are on the order of nano-size [18]. Dust grains are an important component of the circumstellar envelope even though they represent only about 5% of the mass surrounding the star because they help lift gas molecules away from the star through “dust/gas coupling” (see section 1.4). The dust grains drive the wind and, hence, the mass lost from the star.

Dust grains absorb light across many wavelengths but re-radiate at infrared wavelengths. For example, Fig. 1.3 shows the absorption and scattering opacities per gram of gas for the Mathis, Rumpl and Nordsieck (MRN) dust model which
has been used to model interstellar extinction. The MRN dust mixture employs a grain size distribution of 0.005\(\mu\)m to 0.25\(\mu\)m and includes optical properties for both graphite and silicates [22]. For comparison, peak emission for a ‘cool’ star (\(T_{\text{eff}} = 3000\text{K}\)) is 966 nm (~1 \(\mu\)m). The plot shows that this mixture of dust grains would absorb well (\(\kappa_{1\mu\text{m}} > 10\)) at the star’s peak emission.

The IR surface brightness distribution is a measure of mass distribution because dust thermal emission is proportional to density along the line of sight. IR observations can thus reveal the spatial distribution of the dust in the shell. We can estimate dust mass from the surface brightness of the shell (see section 2.4.3). Cold dust is the best choice for imaging the outer boundary of the circumstellar dust shell. Cold dust emission from the outer boundary of the shell reveals information about the mass loss history and also allows us to study the region of interaction between the CDS and ISM. The cold dust grains are heated (to 20-40K) by the interstellar radiation field and re-radiate in the infrared. Dust emission at 70\(\mu\)m probes ~40K dust most effectively via Wien’s law.

### 1.4 Dust-driven winds

When dust grains form in the circumstellar envelope surrounding a star, radiation from the star is absorbed by the grains. For many sources, the opacity blocking the flow of radiation is low so that much of the radiation from the star escapes through the dust. When a dust grain absorbs a photon, it acquires the energy of the photon and heats up. The grain may then lose energy by isotropically re-radiating. The grain also absorbs the momentum of the photon, \(h\nu/c\), where \(h\) is Planck’s constant, \(\nu\) is the frequency and \(c\) is the speed of light. In general, a larger number of photons are traveling radially away from the star, so the net transfer of momentum is radial and the dust grain is accelerated away from the star. Scattering can also transfer momentum to the dust grain. Dust grains drift radially outward
Figure 1.3: The absorptive $\kappa_\lambda$ and scattering $\sigma_\lambda$ opacity of grains in units of cm$^2$ g$^{-1}$ as a function of wavelength for a distribution of grains that follow the Mathis, Rumpl and Nordsieck (1977, hereafter MRN) mixture: a grain size distribution of 0.005$\mu$m to 0.25$\mu$m and a mixture of graphite and olivine. Opacities for graphite and silicates are plotted separately. (From Wolfire & Cassinelli, 1986 [23])

through the surrounding gas and can drive the gas outward through collisions that transfer momentum to the gas molecules. Dust grains can absorb radiation over a wide range of wavelengths, so a continuum of radiation drives the wind (see Fig. 1.3).

1.5 Why the AGB is important

Habing calculates that 95% to 98% of dying stars are low- to intermediate- mass AGB stars with the remainder of objects high-mass stars that may become supernovae [9]. AGB stars contribute to the enrichment of the ISM with dust and gas [24, 25]. AGB stars are by far the most efficient sources of circumstellar dust of the various types of stars that inject dusty matter into the ISM [26]. They are likely the main producers of interstellar dust particles and they are therefore important for the birth of the next generation of stars. Stellar chemical composition is influenced
by the chemical composition of the ISM, and so new stars are influenced by AGB
dust. Lastly, AGB stars directly contribute to the amount of carbon in the Galaxy
[27].

1.6 Infrared space observatories

Two far-infrared (far-IR) space-based observatories of note predated the Spitzer
Space Telescope: the Infrared Astronomy Satellite (IRAS), a joint project of the
US, UK and the Netherlands launched in January of 1983; and the European Space
Agency (ESA) Infrared Space Observatory (ISO), an astronomical observatory that
was operational between November 1995 and May 1998. IRAS was tasked with
building an all-sky survey to identify infrared sources. The instrument was a single
element detector, but its images, including the first all-sky infrared map of the Milky
Way, revealed a startling new view of the universe. The spectrometers onboard ISO
enabled scientists to explore the chemical composition of the universe in greater de-
tail. These observatories are especially notable because the wavelengths they probed
are only visible from space. Earth’s atmosphere absorbs most infrared wavelengths
- preventing them from reaching the ground - and a space telescope is needed to
detect this kind of radiation invisible to the human eye and to optical telescopes.
In addition, far-infrared observatories can probe through dust that obscures optical
wavelengths to reveal structure not visible to the naked eye.

IRAS images illustrated the existence of extended circumstellar dust shells around
certain types of evolved stars, but low resolution prevented detailed examination of
structure. Stencel et al. [28] discovered extended circumstellar emission at 60 µm
for red supergiant stars and supergiant stars in OB associations. Young et al. [29]
identified extended emission for dozens of sources using IRAS 60µm data. Waters et
al. [30], Izumiura et al. [31] and Hashimoto et al. [32] resolved the structure of a few
circumstellar dust shells using high resolution IRAS image processing techniques.
Izumiura et al. detected a large detached circumstellar dust shell surrounding carbon star Y Canum Venaticorum (Y CVn) using ISO/ISOPHOT [33].

Two new space-based far-IR observatories, in addition to the Spitzer Space Telescope, have imaged extended dust shells with greater resolution than IRAS and ISO. Observations made with the superior resolution of the Infrared Camera (IRC) and the Far-Infrared Surveyor (FIS) [34] onboard the AKARI spacecraft [35] have identified extended shells surrounding several sources with unprecedented resolution in the mid-IR [36] and the far-IR [37, 38, 39]. These objects reveal various morphologies, including bow shock structure [39], a detached hollow shell [37] and departures from circular symmetry [38]. The guaranteed time program, Mass loss history of Evolved starS (MESS), used the Photodetector Array Camera & Spectrometer (PACS) and the Spectral and Photometric Imaging Receiver (SPIRE) instruments onboard the European Space Agency (ESA) Herschel telescope to observe more than a hundred evolved stars. Early results of the Herschel MESS program revealed spherically symmetric shells surrounding several carbon stars. [40, 41].

1.7 Probing gas and dust at other wavelengths

Researchers have probed gas and dust surrounding evolved stars at wavelengths other than the infrared. Dust surrounding evolved stars has been imaged in reflected starlight using both a ground-based telescope [42] and the Hubble Space Telescope [43]. Those studies revealed circularly symmetric, but sometimes clumpy, morphologies surrounding the objects imaged. Astronomers have probed the gas surrounding evolved stars, primarily by observing CO rotation lines in spectra using ground-based interferometers in sub-mm wavelengths. Early CO observations revealed detached extended gas shells surrounding several carbon stars. Detached shells were taken as evidence for episodic mass loss, attributed to helium shell flashes (e.g. [44, 45, 46]). More recent CO observations suggested that the gas
envelopes around late AGB stars were mostly spherical, but some were asymmetric (e.g. [47, 48]). Gas studies using SiO and water masers found clumping in some maser regions (e.g. [49, 50]). Lastly, several interferometric studies in the near-IR showed evidence for large inhomogeneities in a few dust shells which, in some cases, may be attributed to magnetic fields and/or stellar rotation (e.g. [51]).

1.8 Estimating dust mass

Several authors have estimated dust mass in shells surrounding carbon stars (e.g. [33, 31]), oxygen-rich stars (e.g. [6]) and proto-planetary nebulae (e.g. [52, 53]) using far-IR and mid-IR (e.g. [36]) observations. Details of a few models and comparisons to the model adapted in this thesis are presented below.

Gillett et al. estimated the mass of dust in the circumstellar shell surrounding R Coronae Borealis (R CrB) using IRAS pointed observations at 12\,\mu m, 25\,\mu m, 60\,\mu m and 100\,\mu m [54]. The authors fit the observations with a simple model for the spatial distribution of radiating material in the shell, assuming optically thin extended emission. They determined integrated properties of the extended emission at 100\,\mu m and then estimated the dust mass using six different dust grain models. The dust temperature was calculated from the flux ratio, \( f_\nu(60\mu m)/f_\nu(100\mu m) \); the effective solid angle subtended by the emitting dust was calculated as \( \Omega_d = f_\nu(\lambda)/B_\nu(\lambda,T) \); and the dust mass was then given by \( M_d = \Omega_d D^2/\kappa(\lambda) \), where \( f_\nu \) is the observed flux, \( B_\nu(\lambda,T) \) is the blackbody intensity, \( D \) is the distance to the star, and \( \kappa(\lambda) \) is a mass absorption coefficient of the form \( \kappa(\lambda) \propto \lambda^{-m} \). The authors estimated total mass by assuming a gas-to-dust ratio of 250 for carbon grains or 200 for silicates. They calculated a total mass in the extended shell surrounding R CrB as \( \sim 0.3 \, M_\odot \) assuming a mass absorption coefficient appropriate for high efficiency (m\approx1) silicate or amorphous carbon grains and solar abundances.
Several authors have adopted the model proposed by Gillett et al. to estimate the mass of dust in circumstellar shells (e.g. [6, 53, 55].) For example, Do et al. adopted the derivation of Gillett et al. in their analysis of far-IR extended emission surrounding three proto-planetary nebulae using Spitzer 70\(\mu\)m and 160\(\mu\)m observations [55]. They assumed a 1/r\(^2\) density profile appropriate for constant mass loss (as in [33, 31]) and a constant escape velocity of \(v_{\text{esc}}=15\ \text{km s}^{-1}\). They also assumed that the dust was composed of small astronomical silicate grains with \(\kappa_\nu = 104 \text{ cm}^2\ \text{g}^{-1}\) at 70 \(\mu\)m (derived from grain radius, \(a=0.1\ \mu\)m; grain density, \(\rho=2.3\ \text{g cm}^{-3}\); and absorption efficiency, \(Q_{\text{abs}}^{\nu} = 2.99 \times 10^{-3}\)). The authors assumed a constant temperature of 26K throughout the shell and a gas-to-dust ratio of 200 in their analysis. The Gillett et al. model was similarly adapted for the calculation of dust mass in this thesis (section 2.4.3) and was also adapted for determining the surface brightness profile of a constant mass loss shell (section 2.4.4).

Izumiura et al. fit a detached shell model to ISOPHOT observations of Y Canum Venaticorum (Y CVn) at 90 \(\mu\)m and 160\(\mu\)m, and a double detached shell to HIRAS observations of U Antuliae (U Ant) at 60\(\mu\)m and 100\(\mu\)m [33, 31]. In their model, the mass density was set proportional to the inverse-square of distance to the star, the expansion velocity was assumed constant (\(v_{\text{exp}}=15\ \text{km s}^{-1}\) for Y CVn and \(v_{\text{exp}}=21\ \text{km s}^{-1}\) for U Ant) yielding a constant mass loss rate. The authors further assumed the dust shell was spherically symmetric, optically thin and in thermal equilibrium with the radiation from the central star. They adopted a grain cross section at 60\(\mu\)m, \(\kappa_{60\mu m}\), of 150 cm\(^2\) g\(^{-1}\), and a dust-to-gas mass ratio of 4.5\times 10^{-3} (carbon-rich chemistry was assumed for both stars). Surface brightness was integrated along the line of sight (see section 2.4.4 for a simpler model with similar integration.) The total mass in the shell was estimated to be in the range \(4 \times 10^{-2} \ M_\odot\) to \(14 \times 10^{-2} \ M_\odot\) for the most reasonable fits to the Y CVn data, but the model did not converge well and yielded several solutions for the shells surrounding U Ant.
Izumiura et al. fit the extended dust shell of the carbon star U Hydrae (U Hya) observed with AKARI FIS at wavelengths 65\(\mu\)m, 90\(\mu\)m, 140\(\mu\)m, and 160\(\mu\)m simultaneously in the four bands with a simple model of a spherical, detached dust shell [37]. The dust mass density, \(\rho(r)\), and dust grain absorptivity, \(\kappa(\lambda)\), were both modeled as power law distributions. The dust absorptivity at 100\(\mu\)m, \(\kappa_{100}\), was fixed at 25 cm\(^2\) g\(^{-1}\) and the expansion velocity, \(v_{\text{exp}}\), was fixed at 15 km s\(^{-1}\). Five free parameters were used to calculate the model brightness profile at each band: \(R_{\text{in}}\), \(\Delta R\), \(\alpha\), \(\beta\), and \(\rho_0\), the inner radius of the shell, width of the shell, power law index for the mass density distribution, power law index of the dust absorptivity, and the initial density, respectively. The dust temperature at the inner edge of the shell was calculated from the effective temperature and luminosity of the star, \(\beta\) and \(R_{\text{in}}\). The temperature distribution inside the shell was also modeled with a power law distribution (dependent on \(\beta\)).

The authors found that two parameters: \(R_{\text{in}}\) and \(\beta\), were well-constrained by the fitting, and that three parameters: \(\Delta R\), \(\alpha\), and \(\rho_0\) converged, but were not as well constrained because the shell’s effective width was smaller than the spatial resolution of the FIS instrument and the model PRF was deficient at \(r \geq 50''\). Dust mass estimates were fairly constant across the fittings, yielding an estimate of \(0.9 \times 10^{-4} (\kappa_{100}/25)^{-1} M_\odot\) to \(1.4 \times 10^{-4} (\kappa_{100}/25)^{-1} M_\odot\) in the shell and a mass loss rate estimated at \(1.8 \times 10^{-8} (\kappa_{100}/25)^{-1} (v_{\text{exp}}/15) M_\odot \text{yr}^{-1}\) to \(9.6 \times 10^{-8} (\kappa_{100}/25)^{-1} (v_{\text{exp}}/15) M_\odot \text{yr}^{-1}\).

Dayal et al. fit near-IR (8\(\mu\)m - 21\(\mu\)m) observations of two proto-planetary nebulae with a two-shell model that consisted of an inner cylindrical warm shell surrounded by an outer spherical cold shell [52]. They assumed the shells were optically thin and adopted a gas-to-dust ratio of 200 for the total mass estimate. The authors constructed temperature and optical depth maps as well as surface brightness maps for each object using the near-IR data, but further constrained the model param-
eters by including mid-IR and IRAS far-IR spectral energy distribution (SED) fits in their analysis. The authors noted that including a temperature gradient through the shell did not improve the model fit.

The examples presented here illustrate that dust mass may be estimated using relatively simple models, particularly for shells that exhibit spherical symmetry. Spherical symmetry is an important consideration because the models presented above assumed spherical symmetry and because most of the fits were made to azimuthally-averaged surface brightness data (e.g. [31, 33, 37, 54, 55]). Some authors used the geographic center of the distribution, rather than the star center in their analysis (e.g. [33, 37]). Spherical symmetry was assumed and azimuthal averages were employed in the dust mass calculations presented in this thesis (see section 2.4.3).

Constant temperature may be reasonable assumption when estimating dust mass from surface brightness measurements in the far-IR because a dust temperature gradient did not play a significant role in estimating dust mass for an extended shell for several models. For example, Dayal et al. omitted temperature gradients from their models after testing both approaches [52]. Izumiura et al. found that dust mass was approximately proportional to the amount of observed emission under the employed dust temperature law that varied slowly with distance from the central star [37]. Gillett et al. found that the dust temperature of the extended shell surrounding R CrB was nearly constant [54]. Constant temperature was assumed in the dust mass calculations in this thesis (see section 2.4.3).

Izumiura et al. noted that the uncertainty in dust absorptivity, $\kappa_\nu$, and expansion velocity, $v_{\text{exp}}$, introduced the most uncertainty in their dust mass calculation [37]. Gillett et al. calculated dust mass using six dust grain models and constrained their results, in part, using assumptions about the initial mass of the star [54]. This thesis adopted the dust opacity at 70\,\mu m employed by Ueta et al. in their analysis of
the extended emission surrounding R Casseopeiae (R Cas) ($\kappa_{70\mu m} = 41$ cm$^2$ g$^{-1}$) for oxygen-rich stars and an opacity ($\kappa_{70\mu m} = 106$ cm$^2$ g$^{-1}$) calculated from Mie theory (assuming amorphous carbon with grain radius: $a=0.1\mu m$) for the carbon stars in the sample. A simple average was used to estimate the opacity ($\kappa_{70\mu m} = 74$ cm$^2$ g$^{-1}$) for S stars. The expansion velocity used in the thesis was an average of CO observations (see table 3.2).

Total mass estimates may vary because of the range of gas-to-dust ratios employed in the models. For example, Gillett et al. adopted a gas-to-dust ratio of 250 for carbon grains and 200 for silicates in their analysis of R CrB [54]. Cox et al. adopted a gas-to-dust ratio of 160 for oxygen-rich stars and 400 for carbon-rich stars in their analysis of 13 sources imaged in the far-IR by AKARI [53]. They assumed the presence of polycyclic aromatic hydrocarbon (PAH) molecules in the carbon shells and suggested that a gas-to-dust ratio of 200 could be used for carbon chemistry without PAH molecules. Izumiura et al. adopted 222 as the gas-to-dust ratio for two carbon stars in their studies using IRAS and HIRAS data [33]. Several authors have adopted a gas-to-dust ratio of 200 for proto-planetary nebulae (e.g. [52, 55]). Ueta et al. found a gas-to-dust ratio of 100 to 500 in their analysis of the oxygen-rich star, R Cas [6] and adopted a gas-to-dust ratio of 150 in their analysis of the planetary nebula NGC 650 [56]. We adopted a gas-to-dust ratio of 150 for silicates and 200 for carbon grains because these values were generally consistent for stars with similar chemistry.

Finally, the most robust results in these examples occurred when fits were made to models across multiple wavelengths or when SED fits were used in conjunction with model shell fits to surface brightness data. For example, Izumiura et al. found good convergence in the parameter space when fitting across four far-IR bands in their analysis of AKARI data for U Hya [37]. Gillett et al. employed SED fits (including mid-IR and far-IR data) to help constrain characteristics of the inner dust...
shell of R CrB [54]. Dayal et al. employed both model shell and model SED fits to define the morphology of the shell and the contribution of cool dust for the two PPNe in their study [52]. The dust masses estimated for shells in this thesis were derived from a very simple model that did not consider multiple wavelengths. In addition, the central portion was missing in each of the maps, so any dust mass estimate is a lower bound (see sections 2.4.3, 3.8.5 and 4.1 for further discussion).

1.9 AGB wind-ISM interactions

Evidence of interactions between circumstellar matter and the interstellar medium around AGB stars is growing, both from recent observations and from theoretical models. For example, a stellar-wind bow shock may form a mass-losing star moves through a medium with a velocity that exceeds the local sound speed [57]. The interaction of the wind with the surrounding material produces a structure that qualitatively resembles the flow around a supersonic body in the Earth’s atmosphere. In a model proposed by Van Buren et al. the stellar wind expands freely in all directions until it meets a terminal shock [57]. The stand-off distance, \( l \), is the distance from the star to the inner edge of the shock and occurs where the momentum flux of the wind equals the ram pressure of the ambient medium. Ueta et al. identified a bow shock structure around R Hydrae (R Hya) [58]. The bow shock structure surrounding R Hya was well-fit with the model, \( y = x^2/3l \), proposed analytically by Van Buren et al. and shown numerically by Mac Low et al. [59] for regions near the apex of the bow shock.

Wareing et al. modeled R Hya and its surroundings using a three dimensional hydrodynamic simulation [60]. The simulation was performed in the frame of reference of the star; the motion of the star through the ISM was like an oncoming wind in the star’s frame of reference. The AGB wind parameters of the model were set with a gas mass-loss rate of \( 3 \times 10^{-7} \, M_\odot \, \text{yr}^{-1} \) and a wind velocity of 10 km s\(^{-1}\).
The ISM was modeled as a warm neutral gas medium with a temperature of $8 \times 10^3$ K. The observed stand-off distance was used to predict the local ISM density used in the model ($n_H=0.6 \text{ cm}^{-3}$). The simulation reached a stable state in 25,000 years. In addition to the bow shock structure, the simulation predicted the existence of a tail of ram-pressure-stripped AGB material stretching downstream from the apex. The authors noted that the ‘bow shock and tail’ structure was convergent for various space velocities (the three-dimensional velocity of the star) and wind parameters. The authors further noted that the bow shock would have destroyed any mass-loss history older than $10^4 \text{ yr}$, but that a higher mass-loss rate and/or lower ISM density could increase the time-scale of the mass loss history.

Observations of Mira in the ultraviolet revealed a bow shock and a turbulent wake extending over 2 degrees in the sky [61]. The authors attributed these structures to Mira’s large space velocity (130 km s$^{-1}$) and the interaction between the wind and ISM. Ueta et al. spatially resolved the astropause (the stellar analog of the heliopause) of Mira using Spitzer observations in the far-IR [62]. The astropause is a cometary stellar wind cavity bounded by the contact discontinuity surface between the wind and the ISM [63]. Contact discontinuities are surfaces that separate zones of different density and temperature$^1$. A contact discontinuity surface is in pressure equilibrium and no gas flows across it; however, van Marle et al. have shown in hydrodynamical models that dust grains may move across a contact discontinuity [64]. In these models, the penetration of the grains into the ISM was size dependent. Small grains (radius: $a<0.045\mu\text{m}$) remained coupled to the gas and piled up at the contact discontinuity, intermediate size grains ($a=0.0284\mu\text{m}$) followed the forward shock, and large grains ($a=0.105\mu\text{m}$) penetrated into the ISM.

Villaver et al. created two-dimensional numerical simulations of the evolution of a low-mass ($1 M_\odot$) star moving supersonically through the ISM [65]. They consid-

---

ered the evolution of the star from the AGB through the PN stage. They found that conservative conditions assumed for the ISM density \(n_0 = 0.01 \, \text{cm}^{-3}\) and \(n_0 = 0.1 \, \text{cm}^{-3}\) and the central star’s velocity \(20 \, \text{km s}^{-1}\) yielded asymmetries in the shells surrounding the objects. The authors noted that bow shock-like and cometary structures should be present unless the star is at rest with respect to the ISM or if the star is moving at low angles with respect to the line of sight.

Waring et al. demonstrated that bow shock and tail structures may form even when the mass-losing central star is moving at low speeds relative to the ISM \((v_{\text{ISM}}=25 \, \text{km s}^{-1}, \dot{M}=5 \times 10^{-7} \, M_\odot \, \text{yr}^{-1})\) and for low ISM density \((n_H=0.01 \, \text{cm}^{-1})\) [66]. The authors developed a ‘triple-wind’ three-dimensional hydrodynamic simulation that included a slow AGB wind \(v_{\text{sw}}=15 \, \text{km s}^{-1}\), a fast post-AGB wind \(v_{\text{fw}}=1000 \, \text{km s}^{-1}\) and a third wind reflecting the linear movement of the star through the ISM \((v_{\text{ISM}})\). The study considered a wide range of stellar velocities, mass-loss rates and ISM densities. The simulations ran from the beginning of the AGB through the PN phase, but assumed constant mass loss rates in each phase.

In addition to bow shock and tail structures, their models showed evidence of turbulence in the tail structures for central stars with higher relative velocities \((v_{\text{ISM}} \geq 50 \, \text{km s}^{-1})\), higher AGB mass loss rates \((\dot{M}=5 \times 10^{-6} \, M_\odot \, \text{yr}^{-1})\) and when the ISM was more dense \((n_H=2 \, \text{cm}^{-3})\).

Recent observations by Herschel identified two cases of ISM interaction with the stellar winds of AGB stars [67]. These shells revealed structures along the outermost filaments which could be turbulent vortices, and both shells exhibited the presence of a clump located in the direction of the space motion. The authors noted that the clumpy feature could be the signature of instabilities arising in the shock front between the ISM and the AGB wind. Such instabilities have been predicted by numerical simulations [68].
Chapter 2

Methodology

2.1 Introduction

This section briefly describes the Spitzer space telescope and instruments onboard the spacecraft and gives detailed information about the post-processing that we performed using both custom IDL scripts and software provided by the Spitzer Science Center (SSC). The section also describes our data reduction, image creation and image analysis techniques.

2.2 Telescope and instruments

2.2.1 Spitzer Space Telescope

The Spitzer space telescope was launched in 1993 and consisted of a 0.85-meter telescope and three cryogenically-cooled instruments [69]. It was designed to perform spectroscopic observations from 5\(\mu\)m to 40\(\mu\)m in high and low resolution; low resolution spectrophotometry from 5\(\mu\)m to 100\(\mu\)m; and imaging and photometry from 3\(\mu\)m to 180\(\mu\)m with a spatial resolution, for example of, 1''7 at 3 \(\mu\)m, 18'' at 70\(\mu\)m and 40''m at 160\(\mu\)m.
All data used in this thesis were obtained using the Multiband Imaging Photometer for Spitzer (MIPS) (see below) [70].

### 2.2.2 Multiband Imaging Photometer for Spitzer (MIPS)

The Multiband Imaging Photometer for Spitzer (MIPS) contained three separate detector arrays (24\(\mu\)m, 70\(\mu\)m, and 160\(\mu\)m). The detector arrays were comprised of different semiconductors: either arsenic-doped silicon, or gallium-doped germanium (24\(\mu\)m was Si:As, 70\(\mu\)m was Ge:Ga, and 160\(\mu\)m was stressed Ge:Ga). The 24\(\mu\)m detector provided a roughly 5\arcmin-square field of view (FOV) with a pixel size of 2\farcs55 pixel\(^{-1}\). The 160\(\mu\)m array projected to the equivalent of a 0.5\arcmin\times5\arcmin FOV with a pixel size of 16\arcsec\times18\arcsec pixel\(^{-1}\). The 70\(\mu\)m detector array was designed to have a 5\arcmin-square FOV, but a cabling problem compromised the outputs of half the array; the remaining side provided a FOV that was roughly 2\arcm by 5\arcmin with an angular pixel size of 9\arcs84 pixel\(^{-1}\) in the wide-FOV mode. All three detector arrays viewed the sky simultaneously.

### 2.2.3 Stimulator calibration

The Ge:Ga material used in the 70\(\mu\)m far-IR detector array was known to have different time scales for signal response: fast and slow. Slow response artifacts were especially challenging when observing extended emission because they were difficult to identify and remove. In essence, each physical detector element had its own distinct response which had to be considered during the data reduction. The responsivity of the entire array also varied unpredictably when the detector was hit by ionizing particles because the cosmic ray hits caused the slow buildup of residual charge in the detector material. The detector was calibrated regularly (nominally every 2 minutes) using stimulator flashes. The stimulator was a small heater that provided a known amount of energy to the array. Latent signals left by the stim-
ulators were removed during pipeline processing (section 2.2.5) using a functional
fit to their time response. Spurious data from cosmic ray hits were removed dur-
ing pipeline processing and during the mosaic process using the temporal outlier
processing capability provided in the MOPEX software (see section 2.3.2, below).
Cosmic rays were expected to hit the array about once every 12 seconds.

2.2.4 AOT and AOR

MIPS observing sessions were planned using Astronomical Observing Templates
(AOT). There were four templates corresponding to the four modes of operation.
Observing sessions for the Mass Loss History of Evolved Stars (MLHES) program
were planned using the Photometry AOT. In this AOT, the observing sequence
started to the left of the source of interest in instrument orientation and the scan
mirror was moved symmetrically to create a column of images. The spacecraft was
then slewed to obtain another column of images. Stimulator flashes were regularly
inserted into the sequence. The observing sequence pattern was designed to average
measurements over several array pixels to mitigate the effects of cosmic ray hits and
the time variability of the detector arrays.

An Astronomical Observation Request (AOR) was the basic scheduling unit
for Spitzer. An AOR was composed of multiple Data Collection Events (DCEs)
(raw images) that were pushed through the pipeline to create basic calibrated data
files (see section 2.2.5). The AOR for the observations used in this thesis were
designed by Ueta et al. in order to maximize the detection of extended emission
(private correspondence). The mapping scheme was designed to cover both the
entire circumstellar dust shell and an amount of sky from which to obtain sky
background information, while preventing the central star (the targets are brighter
than 20 Jy at 25 µm) from falling onto any of the MIPS detectors. The field size of
at least 1.25 times the estimated CDS was designed to allow sky observations for
background referencing. The AOR was also designed to maximize the number of physical pixels used to detect the extended emission in order to allow for averaging of measurements. A series of photometry mode exposures were designed in a grid defined by the Fixed Cluster-Offsets option. Figure 2.1 shows the MLHES AOR overlaid on a map image. The exposure times for each AOR were calculated in order to achieve the required sensitivities for the emission estimated for each object (see Table 3.1).

2.2.5 Basic Calibrated Data (BCD)

The raw images or DCEs collected during Spitzer observations, along with pointing and housekeeping data, were transmitted to earth from the Spitzer observatory. The raw data underwent level-0 processing at the Jet Propulsion Laboratory (JPL) to produce raw astronomical (FITS) images. The headers of the FITS images contained essential information about the DCEs. Pointing-history files that covered 12-hour time periods were also received at the SSC from JPL; these files were used later to assign celestial sky positions to all DCEs.

The individual calibrated data frames that emerge from the Spitzer pipeline are Level 1, Basic Calibrated Data (BCDs). Each AOR contained many other files, including error files and masks. In addition, each AOR contained both primary and nonprime data. Primary data are from the detector for which the observing was planned. Nonprime data may be collected from the remaining two arrays because all three MIPS detectors viewed the sky simultaneously. The 70µm data discussed here were all collected as primary data.

BCDs are 2-dimensional array data. A stack of BCDs make up a data cube with each BCD corresponding to a slice of time. Stacking BCDs allowed us to determine the time change of surface brightness measured by each physical pixel. From the pixel point of view, these measurements represented sky background and
dust emission as well as stimulator flashes and spurious measurements from cosmic ray hits and point response function (PRF) contamination (see section 2.3.3). In addition, each physical pixel’s sensitivity varied in time. We relied on the BCD pipeline to provide the majority of the calibration (e.g. stim calibration) and to help identify and remove spurious data from cosmic ray hits, but we used time series analysis (see section 2.3.1) to remove residual instrument periodicities. PSF contamination was removed from the entire map after mosaicking.

2.3 Data reduction techniques

We employed a custom IDL script to remove time- and pixel-dependent instrument artifacts from the Basic Calibrated Data (BCD) files in order to optimize detection of the faint extended shells. This script was originally developed by T. Ueta to reduce data from the MIPS IR Imaging of AGB Dust shell (MIRIAD) project (PI: A. Speck). Initial Lomb Scargle incorporation was done by a summer student, A. Karska. I made several important modifications to the original script. I replaced an algorithm that was not working with calls to a Lomb Scargle routine provided by ITT Visual Information Solutions\(^1\) in IDL version 7.1 and tested our results against an independent statistical analysis tool called Period04 [71] to confirm the presence of periodic frequencies in the time series. I also implemented annulus processing for the determination of sky background to avoid known edge effect issues in Spitzer 70μm maps. I later modified the script to produce a map of sky background (see below). Our IDL script was effective at removing sky background from each BCD (see Fig. 2.2) Sky subtraction was critical to the data reduction because sky emission must be removed from each map to facilitate accurate photometric measurement of shell emission.

2.3.1 Lomb Scargle periodogram

The heart of our data reduction script is time series analysis using the Lomb Scargle Periodogram. The Lomb Scargle Periodogram is a least-squares frequency analysis technique used to detect periodic signals hidden in noise. The technique was developed by Lomb [72] and enhanced by Scargle [73]. Horne and Baliunas [74] discussed how to correctly calculate variance and how to recalculate the periodogram once a frequency has been removed from the data. The Lomb Scargle Periodogram is particularly useful when the data are unequally spaced in time, which is characteristic of astronomical data and is certainly true for our 70µm Spitzer data because of time gaps from telescope slewing, and stim flashes, for example. We employed Lomb Scargle frequency analysis to help identify and remove periodicities in our Spitzer data. Frequencies in the data were instrument in origin and were removed because there are no naturally-occurring periodic signals on the timeframes of our observations. Each physical pixel should measure different values for sky emission at different pointing locations, but there should be no periodicities in the measurements because the sky background should not fluctuate on any periodic basis.

2.3.2 Mosaic

We used the MOsaicker and Point source EXtractor (MOPEX) software (version 18.3.3; [75]) to produce the final mosaicked image. MOPEX is a robust parameter driven tool. We carefully selected the optimum parameter values, for example, to remove any remaining cosmic ray artifacts from the mosaicked images. We performed PSF subtraction (see below) using a calibrated image of Ceres. The resulting maps were mosaicked in a pixel scale of 9′.84 pixel$^{-1}$ or 4′.92 pixel$^{-1}$ (sub-pixelized by a factor of 2 from the nominal scale). The larger pixel size was used for sources with very faint dust emission. A few images were heavily contaminated with PSF. In

\footnote{Available at http://ssc.spitzer.caltech.edu/dataanalysis/tools/tools/mopex/}
those cases, we found it more effective to subtract the PSF first and then perform sky subtraction: we used our IDL script to write out sky for each BCD; we mosaicked the sky files into one large map; we then subtracted the sky mosaic from the PSF-subtracted image.

2.3.3 PSF subtraction

The point spread function (PSF) describes the response of an optical system to light from a point source. The point response function (PRF) is a map of the appearance of a point source imaged by the detector array. Light was diffracted by three bipod flexures holding the primary mirror inside the Spitzer telescope to create a complicated six-sided pattern (hereafter PRF) (See Fig.2.3). Wings of the PRF were sometimes present in a mosaicked source map. We removed the PRF from the data to avoid overestimating the mass of material in the circumstellar dust shell.

Müller et al. have shown that asteroids are good PRF calibrators because they are point-like (<1″ angular diameter) and their spectra are largely near-IR and thermal emission at longer wavelengths. In addition, they emit light in the far-IR that is bright enough for the sensitivities of far-IR sensors, but not bright enough to saturate these sensors [76]. Asteroids were used as calibrators for Spitzer MIPS, and were especially important for 160μm calibration [77].

We observed the asteroid Ceres on 2008 February 17 using the same observing template as the MLHES AOR. We mosaicked the Ceres BCDs to create a PRF of the same dimension and shape as our MLHES maps. We scaled the Ceres map by multiplying the entire map by a scale factor, then we subtracted the scaled PRF from the source map and calculated the standard deviation of the resultant image within an annulus region of interest. We iterated this process for different scale factors. We determined the optimum scaling factor by selecting the scaling factor
that resulted in a minimum standard deviation for the PRF-subtracted map. We then scaled the Ceres image by the optimum scaling factor, subtracted the scaled Ceres image from the original source image and used the resultant subtracted image for data analysis (see Fig. 2.3). The PFR was subtracted from an image when the scale factor was greater than or equal to 1% of the Ceres PRF.

2.4 Data analysis

See Chapter 3 for maps of each object. Each reduced map is a 2-dimensional projection of a 3-dimensional object. We made several measurements from the surface brightness data in the maps. First, we determined the radial extent of the shell for morphologies that exhibited some spherical symmetry. From the radial extent of the shell, the distance to the object and an assumed expansion velocity (averaged from CO observations), we calculated the dynamical age of the shell. The dynamical age for a shell is a measure of how far in the past we can probe the mass loss history. The semi-major, semi-minor axes and rotation angle were determined for objects that exhibited elliptical symmetry. We described the position angle for features that had some axial symmetry. Lastly, we calculated total flux and estimated the mass of dust in each shell (see Table 3.3 for shell characteristics and Table 3.4 for dust mass estimates).

2.4.1 Radial profile

We determined the extent of the shell by creating an azimuthally-averaged profile for each source. The step size for the radial binning was determined by the pixel scale of each image. We first determined the distance to the star for each pixel in the image. We binned each pixel according to distance and then calculated the average surface brightness for the bin. Bins closer to the star had fewer pixels than bins farther from the star, but the central region was not imaged, and so even the smallest bin had
several data points for averaging. We selected 2 times the standard deviation (2σ) of the background (which was roughly zero because the sky background had been subtracted from the map) as the edge of shell for maps with 4.92 arcsec pixel$^{-1}$ and 1.5σ for maps with 9.82 arcsec pixel$^{-1}$. The azimuthally-averaged extent of shell is listed in Table 3.3 for each source. A radial profile of U Hya pixel data is given in Fig. 2.4.

2.4.2 Photometry

A final step in our process was to calculate the total flux from the circumstellar dust emission for each map. We defined an annulus larger than the radial extent of the shell in order to capture all of the dust emission for each source. We totaled the surface brightness in the region (the counts) and converted units from megaJansky per steradian [MJy sr$^{-1}$] to units of energy flux (Jansky [Jy]). Each map pixel had a size in arcsec$^2$ based upon the pixel scale used to create the map. We used a conversion factor that one square arcsecond equals 2.3504×10$^{-11}$ steradian. For example, a map with pixel scale of 4.92 arcsec pixel$^{-1}$ has pixels of 24.2064 arcsec$^2$, or 5.6895×10$^{-10}$ steradian. To obtain total flux for a map with this pixel scale, we multiplied the total surface brightness of the shell by 5.6895×10$^{-4}$.

For each pixel value measurement in the resulting 2-D map, there were multiple array pixel readings. The mean coverage for each map pixel was 7.4 to 7.7 physical pixels (for pixel scales of 9.84 and 4.92 arcseconds pixel$^{-1}$, respectively), but the coverage varied from less than one pixel at the map edges to more than 22 pixels for regions of deepest coverage. The pixel coverage was fractional because the physical array was projected onto the plane of the sky when the map was created. An important feature of the pixel coverage is that array pixel readings for any one physical pixel did not overlap on the same location of the sky. This allowed us to
identify and remove spurious data, such as cosmic ray hits, before creating the map (see section 2.3.1).

Each map pixel included a contribution from dust emission as well as a small residual contribution from sky emission which must be removed from the final flux calculation. A map pixel “responds” to incident light the same way for both sky and source emission. We defined a region of the map with background only and no sources, created a histogram of pixel values and fitted a Gaussian curve to the histogram. The Gaussian peak location represented the mean residual sky surface brightness and the standard deviation of the fit was the uncertainty of the surface brightness intensity for the corresponding map. We subtracted the mean sky intensity from each pixel prior to adding the intensity to the total for the map. An aperture was defined (360'' for most maps) that was larger than the estimated extent of the shell. The size of the aperture was adjusted when needed for larger shells and for maps of smaller dimension than the MLHES maps.

**Uncertainty in flux**

A derivation for determining the uncertainty in flux is included below.

First subtract the residual sky from each pixel:

\[ J_{obj_i} = J_{src} - J_{sky} \]  

(2.1)

\( J_{obj_i} \) is the intensity of the \( i^{th} \) pixel, \( J_{src} \) is the intensity of emission from the source at the \( i^{th} \) pixel and \( J_{sky} \) is residual sky emission, assumed constant on a given map. The total surface brightness of the object, \( S_{obj} \), is the sum of the contributions from each map pixel in the aperture:

\[ S_{obj} = \sum_{i=1}^{N} J_{obj_i} \]  

(2.2)
Here $N$ is the number of pixels within the aperture. Convert from units of surface brightness to units of flux:
\[
F_{\text{obj}} = C \times S_{\text{obj}}
\]  
(2.3)

Here $C$ is a conversion factor to convert from surface brightness to flux (see section 2.4.2 for more information). The central portion of the data is missing in most of our maps, so the total surface brightness we calculated is a lower bound. Add uncertainties in quadrature:

\[
\sigma_{S_{\text{obj}}}^2 = \left(\frac{\partial J_{\text{obj}i}}{\partial J_{\text{src}}}\right)^2 \sigma_{J_{\text{src}}}^2 + \left(\frac{\partial J_{\text{obj}i}}{\partial J_{\text{sky}}}\right)^2 \sigma_{J_{\text{sky}}}^2 = 2\sigma_{J_{\text{sky}}}^2
\]  
(2.4)

Here $\sigma_{\text{obj}i}$ is the uncertainty in surface brightness of the $i^{th}$ map pixel, and $\sigma_{J_{\text{src}}}$ and $\sigma_{J_{\text{sky}}}$ are the uncertainties in source and sky measurements, respectively and \(\left(\frac{\partial J_{\text{obj}i}}{\partial J_{\text{src}}}\right)^2 = \left(\frac{\partial J_{\text{obj}i}}{\partial J_{\text{sky}}}\right)^2 = 1\). Calculate the uncertainty in total surface brightness of the object, $\sigma_{S_{\text{obj}}}$, from equation 2.2 in quadrature:

\[
\sigma_{S_{\text{obj}}}^2 = \sum_{j=1}^{N} \left(\frac{\partial S_{\text{obj}}}{\partial J_{\text{obj}j}}\right)^2 \sigma_{\text{obj}j}^2 = N\sigma_{\text{obj}j}^2 = 2N\sigma_{J_{\text{sky}}}^2
\]  
(2.5)

Derive the uncertainty in flux, $\sigma_{F_{\text{obj}}}$, from equation 2.3:

\[
\sigma_{F_{\text{obj}}}^2 = C^2 \sigma_{S_{\text{obj}}}^2 = 2NC^2\sigma_{J_{\text{sky}}}^2
\]  
(2.6)

Finally, obtain the uncertainty in flux:

\[
\sigma_{F_{\text{obj}}} = \sqrt{2NC\sigma_{J_{\text{sky}}}}
\]  
(2.7)

Flux values and corresponding uncertainties are tabulated for each source in Table 3.3.
2.4.3 Mass estimates

Dust grains in the circumstellar shell absorb light across the spectrum emitted by the star, but reradiate in the infrared. In order to estimate the mass in the shell, we made several assumptions. First, we assumed that the dust grains are small (∼0.1μm) spherical blackbody particles that follow the Stefan-Boltzmann law. The grains radiate isotropically and the intensity of light emitted from the blackbody surface is given by the Planck equation. We assumed that the shell is isothermal and is optically thin to radiation at the blackbody temperature so the light may escape the envelope. There is no other source of radiation coming into the shell and no loss between the shell and the detector. Each radiating grain contributes to the total flux. The dust mass of the shell may then be estimated from the total flux (see derivation, below).

The formal solution to the equation of radiative transfer with a constant source function is given by [78]:

\[ I_\nu(\tau) = I_\nu(0)e^{-\tau_\nu} + S_\nu(1 - e^{\tau_\nu}) \] (2.8)

Here \( I_\nu \) is the specific intensity of light, \( I_\nu(0) \) is the initial intensity, \( S_\nu \) is the source function and \( \tau_\nu \) is optical depth at the frequency of emission. In this equation, the initial intensity and the source are diminished by absorption. The source function is the blackbody dust grain emission and the initial intensity is zero because there is no other source of thermal emission:

\[ I_\nu(\tau) = (1 - e^{\tau_\nu})B_\nu(T) \approx \tau_\nu \times B_\nu(T) \] (2.9)

Here we invoked a Taylor expansion of \((e^{\tau_\nu})\) because we assumed that the shell is optically thin \((\tau \ll 1)\). The intensity of the blackbody radiation is given by the
Planck equation:

\[ B_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{\frac{h\nu}{kT}} - 1} \]  
(2.10)

Where \( h \) is Planck’s constant, \( \nu \) is the frequency of light, \( k \) is Boltzman’s constant, \( c \) is the speed of light and \( T \) is the temperature of the blackbody. At the Rayleigh-Jeans limit \( h\nu \ll kT \), and so:

\[ B_\nu(T) \approx \frac{2kT\nu^2}{c^2} \]  
(2.11)

The total flux from the shell is the sum of specific intensity of radiation in the direction of solid angle for each pixel:

\[ F_\nu = \sum_i^N \Omega_i I_{\nu_i} = \sum_i^N \Omega_i \tau_\nu B_\nu(T) \]  
(2.12)

Here \( N \) is the number of pixels and \( \Omega \) is the solid angle subtended by the pixel, and we substituted equation 2.9. The solid angle subtended by each pixel is the area of the pixel divided by the square of the distance to the star, \( D_* \):

\[ \Omega_i = \frac{A_i}{D_*^2} \]  
(2.13)

The optical depth is defined as:

\[ \tau_\nu = \int \rho_i \kappa_\nu \, dl \]  
(2.14)

Here \( \rho_i \) is mass density along the line of sight, \( \kappa_\nu \) is opacity and \( l \) is length along the line of sight. Substituting equation 2.13 and equation 2.4.3 into equation 2.12:

\[ F_\nu = \sum_i^N \frac{A_i}{D_*^2} B_\nu(T) \int \rho_i \kappa_\nu \, dl \]  
(2.15)
Assuming opacity is constant:

\[ F_\nu = \sum_i^N \frac{\kappa_\nu}{D_s^2} B_\nu(T) \int \rho_i A_i \, dl \]  

(2.16)

Assuming isothermal emission:

\[ F_\nu = \frac{\kappa_\nu}{D_s^2} B_\nu(T) \sum_i^N \rho_i \, dV_i = \frac{M_{dust} \kappa_\nu}{D_s^2} B_\nu(T) \]  

(2.17)

Substituting equation 2.11:

\[ F_\nu = \frac{M_{dust} \kappa_\nu}{D_s^2} \frac{2kT \nu^2}{c^2} \]  

(2.18)

Finally we arrive at an equation for mass given the flux, temperature of the dust, distance to the star and frequency of light:

\[ M_{dust} = \frac{F_\nu c^2 D_s^2}{2kT_{dust} \nu^2 \kappa_\nu} \]  

(2.19)

### 2.4.4 Surface brightness model for an extended shell

We derived a model to describe a radial profile of surface brightness by distance for a shell under the assumptions of constant mass loss and constant expansion velocity. The derivation for the model shell is given below (adapted from Gillett et al. [54]). From equation 2.9, the surface brightness distribution \( I_\nu \) for an isothermal, optically thin shell may be written as:

\[ I_\nu \approx \tau \times B_\nu(T) = B_\nu(T) \int \rho \kappa_\nu \, dl \]  

(2.20)

We assume that density follows a power law distribution \( \rho = \rho_o r^{-\alpha} \), that opacity
is constant and we integrate from the center of the shell outward along the line of sight:

\[ I_\nu = 2 \rho_0 \kappa_\nu B_\nu(T) \int_0^{l_{\text{max}}} (l^2 + b^2)^{-\alpha/2} \, dl \tag{2.21} \]

Here \( r = \sqrt{l^2 + b^2} \), \( l \) is the line of sight, \( b \) is the closest approach of the line of sight to the star and \( l_{\text{max}} = \sqrt{R^2 + b^2} \) where \( R \) is the outer radius of the shell. Substituting \( x^2 = l^2 + b^2 \), we arrive at:

\[ I_\nu = 2 \rho_0 \kappa_\nu B_\nu(T) \int_b^R \frac{x^{1-\alpha}}{(x^2 + b^2)^{1/2}} \, dx \tag{2.22} \]

\( \alpha = 2 \) for constant mass loss and constant escape velocity [54], and the integral reduces to\(^3\) for \( b < R \):

\[ I_\nu = 2 \rho_0 \kappa_\nu B_\nu(T) \frac{1}{b} \arccos\left(\frac{b}{R}\right) = \frac{4 \rho_0 \kappa_\nu k T_\nu^2}{c^2} \frac{1}{b} \arccos\left(\frac{b}{R}\right) \tag{2.23} \]

Here we applied the Rayleigh-Jeans limit to the blackbody radiation. The surface brightness is proportional to \( \left[ \frac{1}{b} \arccos\left(\frac{b}{R}\right) \right] \) for constant mass loss and constant escape velocity.

\[ I_\nu = C_\nu \frac{1}{b} \arccos\left(\frac{b}{R}\right) \tag{2.24} \]

Here \( C_\nu \) is a proportionality constant that is frequency dependent.

Model shells were generated using Equation 2.24 for shells with radial extent, \( R \), of \( 100'' \), \( 150'' \), \( 200'' \), \( 250'' \) and plotted in log-log scale in Fig. 2.5. The model shells may be fitted with a power law of \( 1.2 < \alpha < 1.4 \) for most of the central portion of the shell. Deviations away from a power law fit of \( 1.2 < \alpha < 1.4 \) in radial profile plots may indicate a change to mass loss for regions away from the edge of the shell.

---

\(^3\)Integration performed using Mathematica version 7
Figure 2.1: MLHES AOR overlaid on the map of U Hydæ (U Hya) in instrument orientation imaged at 70µm in grayscale. Each pink rectangle represents one BCD which is created from Data Collection Events (DCEs). 160 BCDs were combined to create the map. The dither pattern begins at the upper left. The spacecraft slewed counter-clockwise to image the object. One stimulator flash follows every 12 dithers in this AOR.
Figure 2.2: U Hya imaged at 70µm in instrument orientation. The image on the left is a mosaic without sky background subtraction. The image on the right has been processed through a custom IDL script to remove sky background. The surface brightness for both images is given by the false color scale to the right. Note “edge effect” pixels at the outer boundary of the image on the right. Edge effect pixels have a surface brightness that is greater by several standard deviations than pixels surrounding them.
Figure 2.3: An illustration of the PRF subtraction for one example source: R Cassiopeiae (R Cas). The upper panel is a false color map of R Cas in instrument orientation imaged in 70µm. Notice the characteristic PRF spikes, particularly strong at the top of image. The middle panel is the asteroid Ceres in false color at the same scale. The bottom panel is the map of R Cas after the Ceres PRF has been scaled and subtracted from the original map. The resultant map has far less evidence of PRF contamination.
Figure 2.4: Radial profile plots for U Hya. The top plot is raw pixel data after sky subtraction. Notice the scatter in the surface brightness data beyond \( \sim 350'' \). The bottom plot is average surface brightness by average distance in linear scale. Bin size was determined by the pixel scale used to create the image. Curves were fitted to data in log-log scale (e.g. see Fig. 3.9)
Figure 2.5: Model shells were generated using Equation 2.24 for shells with radial extent, $R$, of $100''$, $150''$, $200''$, $250''$ and plotted in log-log scale in Fig. 2.5. The model shells were fitted with a power law of $1.2 < \alpha < 1.4$ for most of the central portion of the shell mapped for our sources (dashed lines).
Chapter 3

Results

3.1 Introduction

Thirty-six objects were observed at 70μm using the Multiband Imager for Spitzer (MIPS). Of these objects, 19 are oxygen-rich stars, 2 are S stars, 9 are carbon stars and 5 are not AGB stars. Of the five non-AGB objects, one is a variable star of type R CrB (R Coronae Borealis (R CrB)), one is a planetary nebula (NGC 6543), and the remaining 3 objects are proto-planetary nebulae (AFGL 2688, HD161796, and IRAS 16342-3814). We also observed an asteroid, Ceres, for PRF calibration purposes [76]. The variable star, HD163588, was observed by MIRIAD also for PRF calibration purposes. Literature data for each object are given in Table 3.1. The 1σ sensitivity and the average background sky emission (removed during data reduction) are listed in Table 3.2 for each source. Also listed in Table 3.2 is the pixel scale used to create each map. Table 3.3 includes the radial average extent of shell, dynamical age and 70μm flux for each source. The dust mass for each source is listed in Table 3.4.
3.2 Observed Morphologies

Five different types of morphologies were exhibited by the sources in our survey that are characterized by the appearance of the surface brightness distribution and the presence or absence of changes to mass loss identified in an azimuthally-averaged radial profile plot.

The first category of morphology is characterized by a surface brightness distribution that surrounds the star but whose radial profile indicates that there is evidence for pile-up at the edge of the shell. Pile-up is a density enhancement at a shell boundary whose presence may be identified by a surface brightness enhancement. The dominant feature of this morphology is the demarcation of the wind-ISM boundary by the pile-up of material. Evidence for the demarcation is the presence of a ‘tail-like’ structure formed by stripping off of material from the edge of the shell. A morphology with a clearly demarcated wind-ISM boundary is classified as “Pile-Up”.

A second morphological category is characterized by evidence for more than one epoch of mass loss, generally with enhanced mass loss later in the life of the shell. The maps of these objects may exhibit a bright central core surrounded by faint emission, or the surface brightness distribution may be irregular in shape. There may be evidence for pile-up between regions and/or at the edge of the shell. A radial profile plot of this morphology shows a clear change in the mass loss history. The dominant feature of this morphology is the evidence for more than one epoch of mass loss, and so this morphology is classified as “Episodic”.

A third category of morphology is characterized by a surface brightness distribution that appears elliptical. The distribution is elongated along one axis and may be described with the parameters of an ellipse: semi-major axis, semi-minor axis and ellipticity or eccentricity. The dominant feature of this morphology is the apparent axisymmetric mass loss; therefore, this morphology is classified as “Elliptical”.
A fourth morphological category is characterized by no evidence that there has been a change to mass loss and no evidence of pile-up at the edge of the shell. Additionally, the AGB wind-ISM interaction has not contributed significantly to shaping these morphologies. The emission need not be uniform. The dominant feature of this morphology is that the emission is fairly symmetric and there is little evidence that mass loss has changed within the timescale of our observation; hence, this morphology is classified as “Regular”.

The fifth and final morphology is characterized by a wind-ISM interaction that produces a parabolically-shaped density enhancement when viewed from the plane parallel to the axis of motion or a circularly-shaped enhancement when observed directly from the head or rear [60]. A further indication of wind-ISM interaction is that the star is off the center of the shell. The density enhancement may be analytically fit to determine the characteristics of the bow shock cone. Objects categorized with this morphology need not exhibit evidence of collisional heating as long as the conic section may be identified in the map or there is evidence that material is being stripped from the shell by the ISM flow local to the source. The dominant features of this morphology is the characteristic bow shock shape, the star is off the center of the shell, and/or trails of emission, and so this morphology is classified as “ISM Interaction”.

Observations for each source are described below in order of distinguishing characteristic: Pile-Up, Episodic, Elliptical, Regular, or ISM Interaction.
3.3 “Pile-Up” Morphology

3.3.1 U Hydreae (U Hya)

U Hydreae (U Hya) was observed on 2009 February 12. Figure 3.1 (top) shows a false color image of the ring-like, nearly circular dust emission surrounding U Hya. We fit a gaussian to azimuthally averaged ring emission divided into four quadrants of 90°. Each quadrant was centered on a position angle (PA). Position angles in instrument orientation were 0°, 90°, 180° and 270°. These angles correspond to PA 81°, PA 171°, PA 261° and PA 351° when the map is oriented north up. The corresponding fits are: peak at 115″ (width 19″, average peak emission of 25.9 MJy sr⁻¹), peak at 108″ (width 23″, average peak emission of 25.1 MJy sr⁻¹), peak at 101″ (width 27″, average peak emission of 21.9 MJy sr⁻¹) and peak at 104″ (width 27″, average peak emission of 21.2 MJy sr⁻¹). These fits indicate that the peak emission is not symmetrically located with respect to the star and that the width and strength of the peak also vary within the ring.

We measured the radial average 2σ edge of the shell at 162″±4″ from the star, which corresponds to a crossing time of 1.8 × 10⁴ yr, assuming constant expansion at 8.6 km s⁻¹ and distance of 208 pc [79]. An elliptical fit to the 2σ edge of the shell showed the ring is distorted from circular symmetry when measured from star center. The fit yielded a semi-major axis of 153″, semi-minor axis of 142″ pixels and eccentricity of 0.37. This region strongly delineates the boundary between the ISM and the edge of the shell (see discussion, below). We also found that the surface brightness distribution is not centered on the star, but is offset by ∼16″ to the northwest.

In addition to the ring structure, our map revealed excess emission to the north-west that looks like a turbulent wake stripping off from the shell proper. A turbulent wake structure has been observed in Mira [61, 62]. The wake is largely symmetric
along an axis at position angle 292° from the star determined by minimizing residuals to parabolic fit centered along varying axes. The wake emission is not an artifact of the data reduction: it is an obvious feature of maps scaled to pixel scales at least four times the nominal scale. The axis of the wake is almost directly opposite the direction of proper motion of the star. Measurements indicate that U Hya has large proper motion in both RA and Dec (42.59 ± 0.24 and -37.72 ± 0.18 mas yr⁻¹, respectively [79]) and a large radial velocity (-25.80 ± 1.7 km s⁻¹ [80]) which yield a greater than average (>43 km s⁻¹) space motion (61.78 ± 1.73 km s⁻¹) that contributes to the removal of material from the edge of the shell.

Figure 3.1 (bottom) includes a radial profile plot of average surface brightness (symbols) by average distance. A gaussian fit to the radial data revealed that the emission peaks at ∼109″ which corresponds to ∼1.2 × 10⁴ yr at the preferred distance, indicating that an enhancement to mass loss may have occurred about this time that lasted ∼7.0 × 10⁴ yr (the crossing time of the shell). A model of constant mass loss is presented for comparison. One most likely explanation for the tail-like turbulent wake structure that we observed is that material is being stripped off the shell by the relative motion of the local ISM flow. Apparently, the relative flow is sufficient to remove material from the shell, but not strong enough to create a bow shock.

U Hya is a carbon star in which the technetium (⁹⁹Tc) absorption line has been detected [81]. ⁹⁹Tc is a short-lived radioactive element (⁹⁹Tc has half-life of about 2 × 10⁵ yr [82]), and is assumed to be produced by s-process nuclear reactions and mixed to the surface late in evolution of AGB stars [8]. Theoretical models suggest that the presence of ⁹⁹Tc is an indication that a star has undergone third dredge-up [82]. Both enhanced mass loss and pile-up may have contributed to the morphology of this shell because the presence of technetium suggests that the star is in the TPAGB when pulsation events may contribute to enhanced mass loss, and
the presence of tail structure suggests pile-up. Pile-up of material at the edge of the shell may have erased mass loss history older than the crossing time of the shell; therefore, if enhanced mass loss contributed to the morphology of this shell, it would have occurred longer ago than $1.9 \times 10^4$ years.

Waters et al. [30] suggested the presence of a detached shell surrounding U Hya at IRAS 60μm using the high resolution maximum entropy image reconstruction technique (HIRAS) [83]. They noted that the dust is not distributed evenly in the detached envelope, but is brighter on the west of the image. They observed a ring of emission that measured a mean distance of $1.75 \pm 0.5$ (105″ ± 30″) at a diffraction limited pixel scale of 1′ and distance of 350 pc. Waters, et al. could not determine the thickness of the shell and attributed the emission to the inner edge of the shell. The ring of emission they observed likely corresponds to the ring structure we observe in our Spitzer map because we calculated the average distance of the peak emission at 107″ which is well-within the error bars of the Waters et al. observation.

Izumiura et al. [38] revealed detailed structure of the circumstellar dust shell in the Far-IR using AKARI FIS at 65, 90, 140, and 160μm and superior pixel scales of 15″ (N60, WIDE-S) and 30″ (WIDE-L, N160). They found a nearly circular, ring-like dust emission centered at the star with a radius of about 130″. The FIS 65μm PSF-subtracted shell image also clearly showed enhancement to the west. Izumiura et al. [42] also observed a very extended circumstellar shell surrounding U Hya in the optical (V band) at 1″5 pixel$^{-1}$. They found an inner shell radius of $\sim$115″ and outer radius of $\sim$130″, which suggests that the optical and far-IR emission are coincident. Lastly, Izumiura et al. note that the mass-loss change in U Hya that took place $\sim$12,000 years ago may be related to a thermal pulse event because U Hya shows evidence of the $^{99}\text{Tc}$ absorption line which indicates a recent third dredge-up [33]. We concur that enhanced mass loss from third dredge-up may have contributed to the morphology of this shell, but we also note that pile-up at
the edge of the shell may be an important contributor to the morphology because it limits the fossil record to the crossing time of the shell.

### 3.4 “Episodic” Morphology

#### 3.4.1 W Hydrae (W Hya)

W Hydrae (W Hya) was observed on 2006 March 03 as part of COASTING (PI: M Morris). The object was observed using two perpendicular scan paths: 15′×3′0 in one direction and 11′×7′7 in the other [55]. The central source was not imaged. Figure 3.2 shows a false color image of the dust emission surrounding W Hya. We observed only a portion of the shell because of the scan map employed but we assume the missing azimuthal data (beyond ∼70″) follows a similar distribution to that shown and that the surface brightness distribution is azimuthally symmetric.

We measured the radial average 2σ edge of the shell at 271 ± 8″ from the star, which corresponds to a dynamical age of 1.5 × 10⁴ yr, assuming constant expansion at 8.3 km s⁻¹ and distance of 98 pc [84]. A large (∼64″ length) far-IR source is visible to the northwest and another smaller (∼24″ diameter) far-IR source is visible to the west. These are not related to the surface brightness distribution from the star because bright emission at the edge of the faint distribution is more likely to be another source in the frame than a product of the mass loss from W Hya. The object to the west is likely a far-IR point source and the larger object may be a galaxy visible in the far-IR.

Figure 3.2 includes a radial profile plot in log-log scale of average surface brightness (symbols) by average distance. A power law fit (dashed line) from the center to an inflection point (∼125″) resulted in an α of 4.5 and delineates the region of enhanced surface brightness centered in the image. A second power law fit (solid line) resulted in an α of 0.4 and delineates the region of lower surface brightness.
extending out to ~225″ surrounding the central bright core. A model of constant mass loss is shown for comparison. The slope deviations from the model suggest that W Hya has experienced at least 2 epochs of mass loss. Initial decreasing mass loss was followed by a more recent enhanced mass loss.

The bright central core of emission of radius ~125″ is surrounded by faint emission to radius ~225″. The core emission is part of the shell and not the star because the stellar contribution was removed by PRF subtraction as part of the data reduction for this source. The epoch of mass loss corresponding to the faint emission occurred at least ~1.5 ×10^4 years ago, lasted ~8.0 × 10^4 years (until ~7 × 10^3 years ago) and was followed by a more recent period of intense mass loss, given our adopted distance. W Hya is a semi-regular pulsating M-type star (sometimes classified as Mira) whose stellar radius has been shown to be highly variable [85]. The technetium (99Tc) absorption line is probably present in this star [82], and so there is evidence of third dredge-up. The most recent mass loss may be the result of enhancement from pulsation events because third dredge-up is an indication that the star has evolved to the TPAGB.

Hawkins observed a large (30′- 40′) (~ 1 pc) symmetric dust shell centered around the red giant W Hya measured by IRAS at 100μm [86]. Hawkins attributed the large apparent size of the shell to several factors, including the proximity of W Hya to Earth and low densities (≤ 0.1 cm\(^{-3}\)) in the surrounding ISM. Our measurements of this shell are an order of magnitude smaller (0.13 pc) but agree with the symmetry described by Hawkins. Gonzales Delgado et al. analyzed circumstellar SiO thermal radio line emission (rotational lines in the ν = 0 state rather than vibrationally excited states) from a large sample of M-type AGB stars [87]. They noted that their data for W Hya were of high quality, but model fits were poor, leading to uncertainties in the properties of the CSE. They concluded that the data for W Hya suggested that the CSE of this star was not typical of others in their study,
possibly because of time-variable mass loss. This source shows evidence of a change to mass loss during its lifetime and supports their conclusion of time-variable mass loss. We categorized this source as episodic because the emission is characterized by a bright central core surrounded by a region of faint emission.

3.4.2 R Lyrae (R Lyr)

R Lyrae (R Lyr) was observed on 2007 October 29. Figure 3.3 shows a false color image of the generally symmetric dust emission surrounding R Lyr. We observed a bright central core of emission of radius $\sim 107''$ surrounded by faint emission to radius $\sim 180''$. The surface brightness in the central region is not uniform; the region is brighter south of the star. We measured the radial average $2\sigma$ edge of the shell at $182'' \pm 2''$ from the star, which corresponds to a dynamical age of $0.8 \times 10^4$ yr, assuming constant expansion at 10.0 km s$^{-1}$ and distance of 91 pc [79]. A far-IR source ($\sim 40''$ diameter) and a smaller second source ($\sim 20''$ diameter) are visible north of the star. These sources are not related to the surface brightness distribution from the star because they are beyond the edge of the shell. They were not included in photometric measurements.

Figure 3.3 includes a radial profile plot in log-log scale of average surface brightness (symbols) by average distance. A power law fit (dashed line) from the center to an inflection point at $\sim 107''$ results in an $\alpha$ of 2.0 and delineates the bright region centered in the image. A second power law fit (solid line) from the inflection point to $\sim 180''$ results in an $\alpha$ of 1.7 and delineates the region of lower surface brightness surrounding the central bright region. The $2\sigma$ edge of the shell is located at $\sim 182''$. A model fit of constant mass loss is plotted for comparison (dot-dash line). The slope deviations suggest that R Lyr has experienced at least 2 epochs of mass loss. The flattening of the log-log plot at $\sim 107''$ corresponds to a surface brightness enhancement. This suggests that two epochs of relatively steady mass loss were
interrupted by a change to mass loss that resulted in this surface brightness enhancement. At our adopted distance, this event occurred $\sim 5 \times 10^3$ years ago and lasted $\sim 9 \times 10^2$ years. It is also possible that the enhanced region is the result of some other physical process such as pile-up or two-wind interaction that results in density enhancement. R Lyr is a semi-regular (SRb) pulsating M-type star [12]. The technetium ($^{99}$Tc) absorption line is probably not present in this star [82], and so there is no evidence of third dredge-up within $2 \times 10^5$ yr. The surface brightness enhancement we observe is likely not the result of third dredge-up but could be the result of thermal pulsation. We categorized this source as episodic because of the presence of a bright inner core emission surrounded by faint secondary emission.

3.4.3 U Antliae (U Ant)

U Antliae (U Ant) was observed on 2006 June 12 as part of MIRIAD (PI: A Speck). The object was mapped with a roughly square region (24′ × 24′) at 70μm and the central 2′ × 1′ were not observed [58]. Figure 3.4 shows a false color image of the dust emission surrounding U Ant. The surface brightness distribution reveals a central region that is nearly circular around the star, but the outer regions are not uniform. In particular, we note a departure from symmetry in faint emission to the southwest beyond $\sim 200''$ and a departure from symmetry in the emission south of the star at $\sim 100''$. We measured the radial average 1.5σ edge of the shell at 204″±4″ from the star, which corresponds to a dynamical age of $1.2 \times 10^4$ yr, assuming constant expansion at 21.0 km s$^{-1}$ and distance of 268 pc [79]. An infrared source to the northwest was not included in photometry because it is outside the radius of the shell.

Figure 3.4 includes a radial profile plot in log-log scale of average surface brightness (symbols) by average distance. A power law fit (dashed line) from the center to an inflection point at $\sim 75''$ resulted in an $\alpha$ of 3.3 indicating a period of increasing
mass loss. Arimatsu et al. observed U Ant in the mid-IR using AKARI IRC on 2006 December 20 and in the Far-IR with AKARI FIS on 2006 December 21[36]. A model fit to these data suggested the presence of two shells: Shell 3 at 43.''5 and Shell 4 at 49.''7. Gonzales Delgado et al. observed U Ant in optical scattered light and proposed the existence of four shells: Shell 1 at 25'', Shell 2 at 36.''5, Shell 3 at 43.''2 and Shell 4 at 46.''1 [88]. CO observations by Olofsson et al. suggested that mass loss for Shell 3 (at 41'') exhibited overall spherical symmetry, but the brightness distribution in the shell is not smooth which suggested clumpiness in the density distribution [89]. They also noted that the shell emission is weaker in the southwest direction. Kerschbaum et al. observed U Ant in the Far-IR with Herschel PACS at 70µm and 160µm [40]. They observed that U Ant has a smooth profile with a detached shell at 43''. They attributed the detached shell to a brief increase in mass-loss some 2800 yr ago, with a subsequent lower mass loss rate. They suggested that this shell coincides with Shell 3 of earlier observations. We note that Shell 1 through Shell 4 in all of these observations are interior to our observations in the far-IR, but the extent of Shell 4 may coincide with the bright central region we observe in our Spitzer map if the inner radius of the shell is ~46'' and the outer radius is ~75''. We further propose that Shell 4 may have formed during a period of increasing mass loss or that pile-up is contributing to the surface brightness enhancement.

A second power law fit (solid line) from ~75'' to ~158'' resulted in an $\alpha$ of 1.8. The 1.5$\sigma$ edge of the shell is located at ~204''. We calculated total surface brightness from 75'' to the outer aperture as 13.0 Jy ± 0.1 Jy. A model of constant mass loss constrained to the size of the shell was fitted to the surface brightness (dot-dash line). The best fit suggests that mass loss has been relatively constant until recently. The change to mass loss began about $4 \times 10^3$ years ago at our preferred distance. Izumiura et al. observed U Ant in the Far-IR using IRAS at 60µm and 100µm [31].
Their data suggested the presence of two shells that they attributed to two thermal pulse events. U Ant is an irregular (Lb) carbon star, and so thermal pulse events are consistent with its evolutionary status. The IRAS 60µm data suggested a faint 2D tail at 2′ to 4′ (120″ to 240″) that they attributed to the outer shell. This shell may correspond to the bright central region (109″ to 165″) in our Spitzer map. At 100 µm they observed asymmetry from 4′ to 6′ (240″ to 360″) with significantly more emission in the northeast side than in the southwest side of the image. This asymmetry may correspond to the asymmetry in faint emission that we observe at 70µm, although our map reveals enhanced faint emission beyond 200″ oriented more to the east than the northeast of the star. We categorized this morphology as episodic because we observed two epochs of mass loss in map and radial profile of this source.

3.4.4 T Microscopii (T Mic)

T Microscopii (T Mic) was observed on 2007 October 28. Figure 3.5 shows a false color image of the dust emission surrounding the oxygen-rich star, T Mic. There is a bright central core of emission and extended faint emission to the south opposite the direction of proper motion. We estimated an extent of the shell of 146″±4″ at 1.5σ of sky background, centered on the star. We deduced a dynamical age of $2.0 \times 10^4$ yr, assuming a constant average expansion velocity of 7.2 km s$^{-1}$ and a distance of 211 pc [79]. Figure 3.5 includes a radial profile plot in log-log scale of average surface brightness (symbols) by average distance. The surface brightness distribution was fitted with a power law fit (dashed line) from the center of the map to 70″ that resulted in an $\alpha$ of 2.4 and a second power law fit from 73″ to 143″ that yielded an $\alpha$ of 1.6. A model fit of constant mass loss is plotted for comparison (dot-dash line). The slope deviation suggests that T Mic has experienced a recent increase to mass loss after an epoch of nearly constant mass loss. At our adopted distance, this event happened $\sim 1.0 \times 10^4$ years ago. The technetium ($^{99}$Tc) absorption line
is possibly present in this star’s spectrum [82] indicating that third dredge-up may have occurred within $2 \times 10^5$ yr. The bright central core of emission surrounded by faint emission is similar to the morphology of R Lyr. The possible presence of $^{99}$Tc suggests that T Mic may have experienced third dredge-up; a dredge-up event could have contributed to the bright central core of emission. An alternative explanation for this morphology is that the surface brightness enhancement results from an ISM interaction; however, we categorized this morphology as episodic because the radial plot suggests that there is evidence for a recent change to mass loss history.

### 3.4.5 X Trianguli Australis (X TrA)

X Trianguli Australis (X TrA) was observed on 2008 April 15. Figure 3.6 shows a false color image of the irregular, not uniform dust emission surrounding X TrA. Three large regions of enhanced emission surround the source; one large accumulation centered to the northeast, one centered to the northwest and a smaller region to the south. These regions are surrounded by faint emission. Each of the larger structures exhibits regions of density enhancement, with the brightest enhancement north of the star and a long arc-shaped enhancement northeast of the star. We estimated an extent of the shell of $186'' \pm 3''$ at $2\sigma$ of sky background, centered on the star. We deduced a crossing time of $3.5 \times 10^4$ yr, assuming a constant average expansion velocity of 9.1 km s$^{-1}$ and a distance of 360 pc [79]. Figure 3.6 includes a radial profile plot in log-log scale of average surface brightness (symbols) by average distance. A power law fit (solid line) from an inflection point at $\sim 142''$ to the edge of shell at $\sim 186''$ resulted in an alpha of 1.9. A model fit of constant mass loss is plotted for comparison (dot-dash line). The slope deviation suggests that X TrA has experienced a decrease to mass loss after an epoch of nearly constant mass loss.

X TrA is classified as a slow irregular, long period variable, carbon rich star [90]). The General Catalogue of Variable Stars (GCVS) lists the spectral type of
X TrA as C5.5(Nb). Kwok et al. classified the spectrum taken by the IRAS Low Resolution Spectrometer (LRS) as C5.5 [91]. Simbad identifies the star as Nova, but this is likely an error because X TrA is not on the IAU Central Bureau for Astronomical Telegrams (CBAT) List of Novae in the Milky Way. We will consider X TrA a carbon star.

Izumiura et al. resolved a detached ring centered on the stellar position surrounding X TrA at IRAS 60 $\mu$m using the high resolution maximum entropy image reconstruction technique [92]. They measured a radius of 2$'$3 (138$''$) and a dynamical age of 2 $\times$ 10$^4$ years. Winters et al. observed CO rotational line spectra of 25 sources, including X TrA [90]. They described two models of mass loss characterized by (A) outflow velocities in excess of 5 km s$^{-1}$ and mass-loss rates larger than 3 $\times$ 10$^{-7}$ $M_\odot$ yr$^{-1}$ and (B) low mass-loss rates, $M \lesssim 3 \times 10^{-7} M_\odot$ yr$^{-1}$, at low outflow velocities, $V_{\text{exp}} \lesssim 5$ km s$^{-1}$. CO(2-1) and (1-0) line profiles suggest X TrA should be classified as a model (A) star, whose winds are driven by radiation pressure on dust.

X TrA is a carbon star in which technetium is probably present [82]. The morphology we observe may be a result of thermal pulsation because X TrA has a comparatively large crossing time (> 3.0 $\times$ 10$^4$ yr) and there is evidence that the star has undergone third dredge-up within 2 $\times$ 10$^5$ yr. We categorized the morphology as episodic because of the change to mass loss suggested by the slope change in the radial profile plot.

### 3.5 “Elliptical” Morphology

#### 3.5.1 RZ Sagittarius (RZ Sgr)

RZ Sagittarius (RZ Sgr) was observed on 2007 October 28. Figure 3.7 shows a false color image of the dust emission surrounding RZ Sgr. The 70$\mu$m emission appears elongated northwest to southeast. We fit an ellipse to the surface bright-
ness distribution and measured a semi-major axis of 162″, semi-minor axis of 116″, eccentricity of 0.70 and position angle 155° for this peak emission (measured at 2σ of background). The star center and center of the ellipse do not correspond; the center of the emission is shifted ∼10″ to the northwest from the star. Faint emission surrounds the peak emission and extends for ∼200″ east and west. We estimated an extent of the shell of 129″ ± 3″ at 2σ of sky background, which corresponds to a dynamical age of 2.1 × 10^4 yr, assuming a constant average expansion velocity of 11.3 km s^{-1} at a distance of 388 pc [90].

Whitelock discovered a reflection nebula surrounding the S star, RZ Sgr, after examining the red (R) and blue (J) films from the ESO/SRC Southern Observatory Southern Sky Survey [93]. Whitelock observed that the optical nebulosity was asymmetric extending further toward the east than the west and with a dense spike toward the southwest. She placed the star at a distance of 1.3 kpc and measured the maximum radial extent of the nebulosity as 1.5 to the east, or 0.5 pc at a distance of 1.3 kpc. She assumed an expansion velocity of 12.5 km s^{-1} and calculated a dynamical age of 4 × 10^4 yr for the 1.5 radius nebula. Whitelock further noted that the optical nebula she observed and an infrared nebula listed in the IRAS Small Scale Structure Catalog are likely related. There is reasonable agreement with the elliptical fit to the Spitzer 70µm data and the radial extent of optical emission noted by Whitelock. Whitelock noted a radial extent of optical emission of 1.5 (90″) to the east and semi-minor axis of 116″ in this Spitzer map.

Ueta et al. have shown that the source of asymmetry in proto-planetary nebulae (PPN) is an equatorial density enhancement present in the innermost regions of the shell [5]. This suggests that a cool, dense disk or torus forms at the transition between the AGB and post-AGB stage [94]. Ueta et al. described the presence of an equatorially enhanced, prolate hollow spheroidal shell that is nearly edge-on in proto-planetary nebulae that are classified as star-obvious low-level elongated
[SOLE]-toroidal PPNs. They note that the degree of equatorial density enhancement determines the detailed PPN shell morphology. The processes that create axisymmetric structures are not well-understood. For example, a sudden enhancement of mass loss near the end of the AGB phase, called the superwind, is thought to remove large amounts of material from the surface of the star and terminate the AGB evolution, but it is not known if the superwind is isotropic [8].

RZ Sgr is a lithium rich, S star classified as SRb variable. Groenewegen et al. noted the presence of technetium on the basis of infrared properties indicating that third dredge-up may have occurred within $2 \times 10^5$ yr.[95]. However, there is no evidence that this source has undergone enhanced mass loss because the radial profile suggests that mass loss has not changed during the past $2.1 \times 10^4$ year (the dynamical age of the shell). There is also no evidence of pile-up at the edge of the shell that could contribute to shaping the morphology. We concluded that the mass loss been axisymmetric because of the elliptical morphology we observed.

3.5.2 V Piscis Austrini (V PsA)

V Piscis Austrinius (V PsA) was observed on 2007 November 28. Figure 3.8 shows a false color image of the dust emission surrounding the oxygen-rich star, V PsA. The shell exhibits an elliptical morphology. There is extended emission southeast of the star in the direction of proper motion that is curved in aspect; emission northwest of the star is less extensive. The distribution appears elongated north to south. We estimated an extent of the shell of $92'' \pm 6''$ at 1.5σ of sky background, centered on the star. We deduced a dynamical age of $0.7 \times 10^4$ yr, assuming a constant average expansion velocity of 19.7 km s$^{-1}$ and a distance of 330 pc [79]. There is evidence for equatorially enhanced mass loss because the surface brightness distribution may be described by an ellipse of semi-major axis $89''$, semi-minor axis of $64''$, eccentricity
of 0.7, and position angle of 100°. We classified this morphology as elliptical because it resembles the elliptical morphology of RZ Sgr.

3.6 “Regular” Morphology

3.6.1 Y Canum Venaticorum (Y CVn)

Y Canum Venaticorum (Y CVn) was observed on 2008 February 17. Figure 3.9 (top) shows a false color image of the dust emission surrounding Y CVn. The surface brightness distribution is nearly circular but is not entirely uniform; for example, the emission is fainter to the west. The surface brightness distribution is not centered on the star, but is offset by \( \sim 21'' \) to the southwest. We measured the 1.4\( \sigma \) extent of the shell as \( 235'' \pm 1.5'' \) from the star, which corresponds to a dynamical age of \( 4.4 \times 10^4 \) yr, assuming constant expansion at 8.1 km s\(^{-1}\) and distance of 321 pc [79]. A far-IR source is visible to the north of the star. We concluded that it is not related to emission from the shell because it is beyond the edge of the shell. The object appears to be a point source in the far-IR and it was not included in photometric measurements.

Figure 3.9 (bottom) includes a radial profile plot in log-log scale of average surface brightness (symbols) by average distance. A power law fit (dashed line) from the center of the map to \( \sim 210'' \) resulted in an \( \alpha \) of 0.5. A model of constant mass loss is shown for comparison. The slope deviation from the model suggests that Y CVn has experienced one eposch of decreasing mass loss.

Y CVn is a J-type carbon star: the photosphere is enriched in \(^{13}\text{C}\) and does not show enrichment of s-process elements [96]. The technetium (\(^{99}\text{Tc}\)) absorption line has not been detected in this star, and so there is no evidence of third dredge-up within \( 2 \times 10^5 \) yr [81]. We observed no indication of enhanced emission in recent
epochs which is consistent in a star that has not recently experienced third dredge-up.

Izumiura et al. observed Y CVn on 25 April 1996 using the ISOPHOT imaging photo-polarimeter instrument onboard the ISO space telescope at 90µm and 160µm [33]. They observed that the extended emission is nearly circularly distributed about the star and that the size of the shell is coincident at both wavelengths. They noted a local maximum at 190″ which they attributed to the inner edge of the shell. We noted a 1.4σ extent of shell of 235″. Izumiura et al. observed a density power-law index of α of 0.83 from simultaneous fittings to the two wavelengths. They revised the power law fit to α of 1.0 after scaling the 90µm data to better match the stellar flux density measured by IRAS at 100µm. Our surface brightness power law index for a similar regime is α of 0.5.

Libert et al. obtained high spectral resolution line profiles of the 21-cm H\textsc{i} emission from Y CVn [97]. They found that there are two expansion velocity components to the gas. They attributed Component 1 (Comp. 1), moving outward at \(\sim\)1-2 km s\(^{-1}\), to the shell. They attributed Component 2 (Comp. 2), expanding at \(\sim\)8 km s\(^{-1}\), to the central infrared source. We adopted an average expansion velocity of 8.1 km s\(^{-1}\) based on several measurements (see Table 3.2), rather than their preferred shell expansion velocity. Our estimate of the crossing time of the shell would be underestimated if the shell is expanding at a slower velocity. Libert et al. modeled the circumstellar shell as an inner, gaseous, freely expanding region, a detached shell that is also freely expanding (with the inner velocity), a region of compressed material, and, finally, an external boundary. If this is the case, the innermost region of our \textit{Spitzer} map (\(<\) 210″) would correspond to the detached shell of their model. We observed no evidence for a compressed region. We categorized Y CVn as a regular morphology because of the single epoch of mass loss.
3.6.2 Y Lyncis (Y Lyn)

Y Lyncis (Y Lyn) was observed on 2008 April 15. Figure 3.10 shows a false color image of the dust emission surrounding Y Lyn. The emission surrounds the star but is not uniform because of faint wing-like extensions to the northwest and south of the star, which may be artifacts of the data reduction. A far-IR source to the northeast and another source to the south are not related to the dust emission from this source because they are beyond the edge of the shell. We estimated the extent of the shell at 145″ ± 8″ at 1.5σ of sky background, centered on the star. We deduced a dynamical age of 2.6 × 10^4 yr, assuming a constant average expansion velocity of 6.7 km s^{-1} and a distance of 253 pc [79].

Figure 3.16 also includes a radial profile plot in log-log scale of average surface brightness (symbols) by average distance. A power law fit from ~124″ to ~145″ (solid line) resulted in an α of 2.2. A model fit of constant mass loss is plotted for comparison (dot-dash line). The fit suggests that Y Lyn has experienced one epoch of mass loss. There is evidence that mass loss has decreased recently (~124″, or ~2.2 × 10^4 years at our preferred distance), but the data are noisy close to the star.

Y Lyn is an oxygen-rich variable (SRa) star in which technetium is probably present [82]. This star may have experienced third dredge-up, but we cannot confirm the presence of multiple epochs of mass loss. Young et al. identified an outer radius of 0.41 pc and an inner radius of 0.13 pc for Y Lyr at a distance of 330 pc [29]. These measurements correspond to an outer radius of 0.31 pc and an inner radius of 0.10 pc at our adopted distance of 253 pc. Our Spitzer observations agree reasonably well with the measurement for inner radius because the edge of shell at ~124″ corresponds to 0.15 pc. The relative ISM flow is likely small near this source because Y Lyn has a small proper motion in RA (-8.92 mas yr^{-1}) and Dec (-7.13 mas yr^{-1}) and the shape of the shell is fairly symmetric. We categorized this morphology as regular because we observe a single epoch of constant mass loss.
3.6.3  V Telescopii (V Tel)

V Telescopium (V Tel) was observed on 2007 October 28. Figure 3.11 shows a false color image of the dust emission surrounding V Tel. The emission around this oxygen-rich star is symmetric but not uniform and appears clumpy. Two far-IR sources may be observed in the image: a point source to the southeast and a larger source south of the star. These sources do not appear to be related to the dust emission from V Tel because they are beyond the edge of the shell. Both were removed for photometry. We estimated an extent of the shell of $155'' \pm 8''$ at 1.2σ of sky background, centered on the star. We deduced a dynamical age of $2.7 \times 10^4$ yr, assuming a constant average expansion velocity of 8.4 km s$^{-1}$ and a distance of 309 pc [79]. Figure 3.11 includes a radial profile plot in log-log scale of average surface brightness (symbols) by average distance. A power law fit (solid line) from $\sim 125''$ to $\sim 155''$ resulted in an $\alpha$ of 1.4 indicating that during this epoch mass loss was steady. A model fit of constant mass loss is plotted for comparison (dot-dash line). There is evidence that mass loss has decreased recently ($\sim 125''$, or $\sim 2.2 \times 10^4$ years at our preferred distance), but the data are noisy close to the star. We categorized this morphology as regular because we observe a single epoch of constant mass loss.

3.6.4  RT Capricorni (RT Cap)

RT Capricorni (RT Cap) was observed on 2007 October 27. Figure 3.12 shows a false color image of the dust emission surrounding the carbon star, RT Cap. The emission surrounds the star but is not uniform. For example, there is surface brightness enhancement in the center and extended slightly to the south of the star in the direction of proper motion. RT Cap has a low average mass loss rate ($6.0 \times 10^{-8}$ M$\odot$ yr$^{-1}$, see Table 3.2) and small measured CSE flux ($\sim 3.5$ Jy), and so it is more difficult to differentiate the features of the map. We estimated an extent of the shell of $105'' \pm 6''$ at 1.5σ of sky background, centered on the star. We deduced
a dynamical age of $1.6 \times 10^4$ yr, assuming a constant average expansion velocity of 9.1 km s$^{-1}$ and a distance of 291 pc [79]. Figure 3.12 includes a radial profile plot in log-log scale of average surface brightness (symbols) by average distance. A power law fit (solid line) from $\sim 95''$ to the edge of the shell ($\sim 105''$) resulted in an $\alpha$ of 1.2. A model fit of constant mass loss is plotted for comparison (dot-dash line). The fit suggests that RT Cap has experienced one epoch of constant mass loss. There is evidence that mass loss has decreased recently, but the missing data makes this region difficult to evaluate. We categorized this morphology as regular because the morphology is similar to V Tel and there is little evidence for a change to mass loss.

3.7 “ISM Interaction” Morphology

3.7.1 R Hydrae (R Hya)

R Hydrae (R Hya) was observed on 2006 February 26 as part of MIRIAD (PI: A Speck). The object was mapped with a roughly square region (24$'$×24$'$) at 70$\mu$m and the central 2$'$×1$'$ were not observed [58]. Figure 3.13 shows a false color image of the dust emission surrounding the oxygen-rich, Mira variable star, R Hya. The surface brightness distribution exhibits a concentric arc that is a parabolically-shaped density enhancement, or bow shock [58] to the northwest from the star. There is also a tail of faint emission in the direction opposite the bow shock.

Hashimoto et al. observed a large (3$'$-4$'$), detached circumstellar shell surrounding R Hya in IRAS 60$\mu$m and 100$\mu$m images produced by the Pyramid Maximum Entropy (PME) image reconstruction technique [32]. The emission appeared almost circular at 60$\mu$m. A detached shell was also noted by Young et al. using IRAS 60$\mu$m data. Ueta et al. revealed a bow shock at the interface of the interstellar medium and the AGB wind from R Hya [58]. Their 70$\mu$m map showed an arclike surface brightness distribution at $>10$ MJy sr$^{-1}$ surrounded by fainter emission ($<10$ MJy sr$^{-1}$).
sr$^{-1}$) of $\sim$400 $''$ diameter around the bright central object. Ueta et al. described the inclined bow shock and also noted a tail of emission downstream from the shock. They obtained a lower limit of 19.4 ± 3.6 Jy for the circumstellar flux at 70$\mu$m using a model PSF. We obtained 20.1± 0.1 Jy with our reduction using an empirical PSF.

3.7.2 RT Virginis (RT Vir)

RT Virginis (RT Vir) was observed on 2008 February 19. Figure 3.14 shows a false color image of the dust emission surrounding RT Vir. The surface brightness distribution not uniform; the surface brightness is enhanced in the direction of proper motion and there is a trail of faint emission opposite the direction of proper motion. We estimated an extent of the shell of 115$''$$\pm$5$''$ at 2$\sigma$ of sky background, centered on the star. There is evidence of a parabolically-shaped density enhancement similar to bow shock structures found in other objects such as R Hya [58]. The bright arc delineates the edge of the shell and there may be some brightening close to the star. We categorized this shell as ISM interaction because there may be a bow shock structure present in this morphology.

3.7.3 SW Virginis (SW Vir)

SW Virginis (SW Vir) was observed on 2008 February 16. Figure 3.15 shows a false color image of the dust emission surrounding the semi-regular, oxygen-rich star, SW Vir. The map of SW Vir shows a nearly central region of bright emission surrounded by fainter not uniform emission. The map shows evidence of a concentric arc that is a parabolically-shaped density enhancement similar to bow shock structures found in other objects such as R Hya [58]. The density enhancement structure is not an artifact of the data reduction because it is scalable; the structure is visible in maps mosaicked at the oversampled 70$\mu$m pixel scale of 4.92$''$ per pixel, the nominal pixel scale of 9.84$''$ per pixel and up to twice the 70$\mu$m nominal pixel scale. The surface
brightness is not uniformly distributed throughout the parabolic region, but shows enhancement to the north and to the northwest. The apex of the parabolic arc is at position angle (PA) 313 degrees. The apex is noticeably offset from the direction of proper motion of the star (PA slightly less than 270 degrees) and is $\sim 280''$ from the star. At the preferred distance of 143 pc, this corresponds to a radial dimension of 0.2 pc from the star to apex of the arc. SW Vir has proper motion in RA of $-36.21\pm0.77$ mas yr$^{-1}$ and Dec of $-2.62\pm0.68$ mas yr$^{-1}$ (Tycho catalog [98]) and a small radial velocity of $-15$ km s$^{-1}$ [80] resulting in a small space motion of 28 km s$^{-1}$. Ueta et al. suggest that a large space motion enhances the probability of detecting a bow shock [58]. SW Vir shows no evidence of a bow shock but the ISM flow local to the star appears to be interacting with the shell to form the cometary shape we observe. There may be evidence of two epochs of mass loss: an earlier epoch now shaped by an ISM interaction and a more recent epoch resulting in the bright central core of emission. We categorized this morphology as ISM interaction because of the cometary shape of the shell.

3.7.4 Y Hydrae (Y Hya)

Y Hydrae (Y Hya) was observed on 2008 January 5. Figure 3.16 shows a false color image of the dust emission surrounding Y Hya. The emission is irregular with brightening north of the star and a possible arc whose apex is toward the direction of proper motion. The emission is faint to the west opposite the direction of proper motion. The missing data at the center of the image may obscure possible bow shock structure suggested by the arc shape to the morphology. One explanation for the morphology we observe is that the shell is being shaped by the relative motion of the local ISM flow resulting in a possible arc with tail structure opposite. We estimated an extent of the shell of $99''\pm3''$ at 2$\sigma$ of sky background, centered on the star. Young et al. identified an outer radius of 1.4 pc and an inner radius of 0.19 pc.
for Y Hya at a distance of 510 pc [29]. These measurements correspond to an outer radius of 1.1 pc and an inner radius of 0.14 pc at our adopted distance of 389 pc. Our Spitzer observations suggest the shell is not as extended as the estimates based on IRAS models because we measured the 2σ extent of the shell as 0.18 pc.

3.7.5 R Casseopeiae (R Cas)

R Casseopeiae (R Cas) was observed on 2008 February 18. Figure 3.17 shows a false color image of the nearly circular dust emission surrounding this oxygen-rich, Mira variable star. Ueta et al. described the morphology of this shell in great detail; he attributed the brightening to the interaction of the shell with an ISM flow local to the star [6]. We estimated an extent of the shell of $176'' \pm 4''$ at 2σ of sky background, centered on the star. We deduced a dynamical age of $1.2 \times 10^4$ yr, assuming a constant average expansion velocity of 12.0 km s$^{-1}$ and a distance of 176 pc [79].

Figure 3.17 includes a radial profile plot of average surface brightness (symbols) by average distance centered on the star for two regions: the enhanced region (circles) and the faint region (diamonds). The combined average is represented by the dashed line. The curves are shifted with respect to each other because the surface brightness distribution is not centered on the star. The average 2σ edge of shell is at $176'' \pm 4''$. Young et al. noted a detached, extended circumstellar shell originally detected by IRAS at $60\mu$m, with an outer radius of 0.27 pc and an inner radius of 0.06 pc at a distance of 220 pc. These measurements correspond to an outer radius of 0.22 pc and an inner radius of 0.05 pc at our adopted distance of 176 pc. We find the shell is not as extended because we measure the 2σ extent of the shell as 0.15 pc.

Ueta et al. obtained far-IR images of R Cas at 65, 70, 90, 140, and 160μm using AKARI and Spitzer. They revealed that the shell is very extended (2′ to 3′ radius,
corresponding to 0.1 pc at a distance of 176 pc) and slightly elliptical \[6\]. They also note that the central star is offset from the geometric center of the shell in the direction of the measured proper motion of the central star. Ueta et al. noted a temperature enhanced region toward the windward edge of the interface of the shell and the ISM but did not identify a clear parabolic bow shock structure. We assign R Cas to the ISM interaction category because it has been shown that the brightening to the east is due to collisional heating of the dust.

3.7.6 RS Cancri (RS Cnc)

RS Cancri (RS Cnc) was observed on 2008 May 16. Figure 3.18 shows a false color image of the dust emission surrounding RS Cnc. The emission is irregular with brightening south of the star and a long trail (\(\sim 235''\)) of bright emission to the northwest of the star (PA \(\sim 310^\circ\)). The trail is not symmetric along the axis, but is distended to the south. The central emission is extended to the southwest almost in the direction of proper motion. We estimated an extent of the shell of 112''\(\pm\)5'' at 2\(\sigma\) of sky background. We placed the direction of proper motion at \(\sim 200''\) based on proper motion in right ascension of \(-11.12\pm0.65\) mas yr\(^{-1}\) (RA) and in declination of \(-33.42\pm0.24\) mas yr\(^{-1}\) (Dec) (Hipparcos, the New Reduction [79]). The central region could be equitorially enhanced emission because it appears somewhat elliptical. Both the central region and the trail of emission appeared to be dust emission from the star because they are coincident and there is no gap between them. An infrared point source is located to the southwest (PA \(\sim 240''\)) and is likely not related to the shell from this source because it is beyond the edge of the shell. RS Cnc is a variable (SRc) S star in whom technetium has been detected [82]. Episodic mass loss is consistent with an AGB star in the later stages of stellar evolution, such as stars that have experienced third dredge-up.
Young et al. identified an outer radius of 0.33 pc and an inner radius of 0.06 pc for RS Cnc at a distance of 200 pc [29]. These measurements correspond to an outer radius of 0.24 pc and an inner radius of 0.04 pc at our adopted distance of 143 pc. Our Spitzer observations agree well with the measurement for inner radius because the inner peak at \( \sim 66'' \) corresponds to 0.05 pc at our preferred distance. Knapp et al. noted the presence of two winds with different outflow velocities in their analysis of RS Cnc CO line emission [99]. They note that the narrow component they observe may be due to the resumption of mass loss after it has been stopped by some change in the stellar properties. There may be evidence of a change to mass loss in our Spitzer map of this source.

Using both CO and HI lines, Libert et al. observed that the circumstellar environment around RS Cnc included two related but well separated regions [100]. They found a central bipolar geometry using CO that they attributed to recent mass-loss processes. We found the central emission to be elongated along the direction of proper motion which may be related to the bipolar geometry they observed. Libert et al. found a trail of gas in H\( \text{I} \) in a direction opposite to the proper motion of RS Cnc at PA \( \sim 310'' \) that they suggested lent support to the hypothesis of an interaction with the interstellar medium. They corrected the proper motion for the solar motion towards the apex to obtain 20 mas yr\(^{-1} \) in right ascension (RA) and -21 mas yr\(^{-1} \) in declination (Dec). We observed a trail of emission in the far-IR that appears to be coincident with the HI gas emission at the same position angle, but we found the trail to be oriented at an angle to the direction of proper motion of the star.

We categorized RS Cnc as a source whose morphology strongly suggests interaction with the ISM because of the extended trail of emission away from the star as was also shown for H\( \text{I} \) emission [100].
3.7.7 X Pavonis (X Pav)

X Pavo (X Pav) was observed on 2007 October 27. Figure 3.19 shows a false color image of the dust emission surrounding X Pav. The map also shows a strong resemblance to other definite bow shock cases. The emission is faint to the west and is brightest in the direction of proper motion of this oxygen-rich star. The apex of the parabolic arc is noticeably offset from the direction of proper motion of the star at PA \(\sim 85''\). The proper motion in RA is \(29.47\pm0.71 \text{ mas yr}^{-1}\) and in Dec is \(-9.87\pm0.97 \text{ mas yr}^{-1}\) [79], and so the relative ISM flow may be substantial enough to contribute to surface brightness enhancement we observe, as with R Cas. The radial velocity component of the motion (-18 km s\(^{-1}\) [80] may contribute to the “tear-drop” shape of the emission. We estimated an extent of the shell of \(138''\pm2''\) at \(2\sigma\) of sky background, centered on the star. We categorized this morphology as ISM interaction because of the bright central region and because the shape of the morphology suggests a trail of emission away from the direction of proper motion.

3.7.8 EP Aquarii (EP Aqr)

EP Aquarii (EP Aqr) was observed on 2007 November 28. Figure 3.20 shows a false color image of the dust emission surrounding EP Aqr. The 70\(\mu\)m emission appears elongated northwest to southeast and is brighter to the south of the star. We fit an ellipse to the surface brightness distribution and measured a semi-major axis of 134'', semi-minor axis of 97'', eccentricity of 0.69 and PA 197° (measured at 1.5\(\sigma\) of background). The center of emission is shifted \(\sim 30''\) to the south from the star. EP Aqr is an M-type (M8III) semi-regular variable (SRb) star with a period of 55 days (General Catalogue of Variable Stars [12]). Dumm and Schild give an effective temperature of 3236K and stellar mass of 1.7 M\(_\odot\) [85]. Lebzelter and Hron did not detect technetium in the spectra of this source [101], which is consistent with a smaller mass star because stars less massive than 1.8 M\(_\odot\) may not progress to third
dredge-up. This star has likely not undergone third dredge-up because the radial profile indicates no change to mass loss.

Winters et al. noted that the circumstellar CO shell of EP Aqr appeared to be roughly spherically symmetric with an extension in the southwest direction [102]. They found no significant deviation from circular symmetry in CO emission and interpreted the composite CO profile they observed as due to two wind components of different velocities: a narrow component corresponding to an outflow velocity of $\sim 1 \text{ km s}^{-1}$ and broad component corresponding to an outflow velocity of $\sim 11 \text{ km s}^{-1}$. The southwest extension of CO emission observed by Winters et al. could correspond to the southwest extension in the far-IR that we observe here.

One possible explanation for the morphology we observe is that mass loss has been axisymmetric for the dynamical age of the shell. Another possible explanation is that the morphology we observe is bow shock structure seen nearly head-on (or from the rear). A parabolic arc is the characteristic shape of a bow shock when viewed from a plane parallel to the axis of motion [66]. A bow shock observed directly from the head or rear would appear circular in the sky [60]. Additionally, there is a large offset ($\sim 30''$) between the star and the center of the emission which is consistent with bow shock structure [60] and the star has a large ($-37.2 \text{ km s}^{-1}$) radial velocity (General Catalog of Stellar Radial Velocities [103]). We classify this morphology as ISM interaction because it resembles other ‘tear-drop’ shaped morphologies, such as X Pav, whose morphology was likely shaped by ISM interaction.

3.7.9 V Pavonis (V Pav)

V Pavonis (V Pav) was observed on 2007 September 19. Figure 3.21 shows a false color image of the dust emission surrounding V Pav. The shell appears elongated north to south. There is a small surface brightness enhancement north of the star in a direction opposite the direction of proper motion that appears curved and a trail of
emission to the south that appears somewhat pointed giving the overall morphology a ‘tear-drop’ shape. Striping in the image is likely an artifact of the data reduction because it is columnar in instrument view. We estimated an extent of the shell of 91″±5″ at 2σ of sky background, centered on the star. We fit an ellipse to the shell and determined that the center of the ellipse is offset from the star, which is an indication of ISM interaction. The dimensions of the ellipse were: semi-major axis of 98″, semi-minor axis of 64″, eccentricity of 0.3 and position angle of 170°. V Pav is a carbon star with a shell of radius 0.16 pc (assuming distance of 370 pc [79]). The average mass loss rate for V Pav is estimated at $3.1 \times 10^{-7}$. X TrA, a carbon star of comparable distance (360 pc) and mass loss rate ($3.8 \times 10^{-7} \ M_\odot$), has a larger shell (0.32 pc). We classified this morphology as ISM interaction because it resembles other ‘tear-drop’ morphologies, such as X Pav.

3.7.10 RV Cygni (RV Cyg)

RV Cygni (RV Cyg) was observed on 2007 November 29. Figure 3.22 shows a false color image of the dust emission surrounding the carbon star, RV Cyg. There is a surface brightness enhancement to the north of the star, extended emission to the east and very little emission to the west of the star. We estimated an extent of the shell of 110″±7″ at 2σ of sky background, centered on the star. The missing data at the center of the image may obscure possible bow shock structure suggested by the morphology. We may be observing a bow shock nearly head-on because the structure to the east of the star is tail-like and there is evidence of brightening near the star. The tail-like extension suggests RV Cyg belongs in the ISM interaction category because the most likely explanation for the structure is that material is being displaced from radial symmetry by the relative motion of the ISM flow local to the star.
3.7.11 TX Piscium (TX Psc)

TX Piscium (TX Psc) was observed on 2008 July 29. Figure 3.23 shows a false color image of the dust emission surrounding the carbon star, TX Psc. The surface brightness distribution is very irregular because there is enhanced emission to the north of the star and a very extended (∼275") trail of emission to the west opposite the direction of proper motion. We estimated an extent of the shell of 96" ± 6" at 1.2σ of sky background, centered on the star. The technetium (99Tc) absorption line is present in this star’s spectrum [82], suggesting that enhanced mass loss from third dredge-up may have occurred within 2 × 10^5 yr. The emission near the star appears enhanced but much of the shell is missing in our Spitzer map, and so we cannot confirm that the star has experienced a change to mass loss. The brightening near the star and long tail-like structure suggest that this morphology should be categorized as ISM interaction.

3.7.12 KK Carinae (KK Car)

KK Carinae (KK Car) was observed on 2008 February 17. Figure 3.24 shows a false color image of the dust emission surrounding KK Car. The emission is irregular with a long trail of bright emission to the northwest of the star opposite the direction of proper motion, similar to the tail structure observed in RS Cnc (see Fig. 3.18). There is little evidence of a bright core or parabolic arc shape because the central portion of the map is missing, and so it is difficult to determine the structure close to the star. We estimated an extent of the shell of 153" ± 19" at 1.2σ of sky background, centered on the star, which is equivalent to ∼0.25 pc at our preferred distance of 342 pc. KK Car is a Mira variable oxygen-rich star with a low proper motion in RA (2.9 ± 3.2 mas yr\(^{-1}\)) and Dec (-1.9 ± 3 mas yr\(^{-1}\)) (Tycho catalog [98]). One explanation for the morphology we observe is that material is being carried away
from the star by the relative motion of the local ISM flow. We categorized this morphology as ISM interaction because of the long trail of emission away from the star.

3.7.13 U Mensae (U Men)

U Mensae (U Men) was observed on 2007 October 27. Figure 3.25 (top) shows a false color image of the dust emission surrounding U Men. The emission is irregular and not uniform with a faint extension to the northeast of the star in the direction of proper motion. U Men has a significant radial velocity of 29 km s$^{-1}$ [104] directed toward us, so the trail of emission may be oriented away from the space motion of the star. It is difficult to determine structure near the star because the central data is missing from the Spitzer map. U Men is a variable (SRa) oxygen-rich star with a low mass loss rate ($2.0 \times 10^{-7}$) [105] and small proper motion in RA ($5.2 \pm 2$ mas yr$^{-1}$) and Dec ($16.9 \pm 1.9$ mas yr$^{-1}$) (Tycho catalog [98]). One explanation for the morphology we observe is that material is being carried away from the star by the relative motion of the local ISM flow. We estimated an extent of the shell of 100$''$±34$''$ at 1.5$\sigma$ of sky background, centered on the star, which is equivalent to $\sim0.10$ pc at our preferred distance of 320 pc. We categorized this morphology as ISM interaction because of the extended trail of emission.

3.7.14 RS Andromedae (RS And)

RS Andromeda (RS And) was observed on 2008 February 16. Figure 3.26 shows a false color image of the dust emission surrounding the oxygen-rich star, RS And. There is emission northwest of the star opposite the direction of proper motion but little apparent emission southeast in the direction of proper motion. RS And has a low average mass loss rate ($1.5 \times 10^{-7}$, see Table 3.2) and a relatively small proper motion in RA ($19.9 \pm 1.1$ mas yr$^{-1}$) and Dec ($-12.4 \pm 1.1$ mas yr$^{-1}$) (Tycho catalog
The emission appears offset from the star, but it is not clear if it is elliptical in shape because of the missing data in the center of the map. We estimated an extent of the shell of $75'' \pm 13''$ at $1.5\sigma$ of sky background, centered on the star, which is equivalent to $\sim 0.10$ pc at our preferred distance of 290 pc. Young et al. identified an outer radius of 2.5 pc and an inner radius of 0.45 pc for RS And at a distance of 440 pc [29]. These measurements correspond to an outer radius of 1.65 pc and an inner radius of 0.36 pc at our adopted distance of 290 pc. The shell size deduced from Spitzer observations is noticeably smaller than those derived from modeled IRAS measurements. We categorized the morphology of RS And as ISM-interaction because the distribution is offset from the center of the star.

3.8 Discussion

3.8.1 Non-detection

We did not detect an extended dust shell at 70\(\mu\)m for two objects: RW Bootes (RW Boo) and \(\rho\) Perseus (\(\rho\) Per), both oxygen-rich stars. Hashimoto et al. fit IRAS data for RW Boo with a model dust shell of inner radius: \(r_{in}=40\ R_\odot\), outer radius: \(r_{out}=3162\ R_\odot\) and inner dust temperature: \(T_d(r_i)=465\text{K} \) [106]. Nyman et al. did not detect CO(1-0) emission surrounding RW Boo [107]. Stencel et al. did not detect extended emission at IRAS 60\(\mu\)m for \(\rho\) Per in their analysis using full width at 10\% maximum (FW.1M) [28]. It is possible that RW Boo and \(\rho\) Per have circumstellar dust shells of radius: \(r \leq 50''\) because our Spitzer maps do not show the central region surrounding each star. The outer limit for age cannot be determined for these shells because CO emission has not been detected.

Our results were inconclusive for four objects that were heavily contaminated with PRF: AFGL2688, IRAS 16432-3814, HD161796 and OH231.8+4.2. Do et al. reported no extended emission for OH231.8+4.2 or AFGL2688. They did detect
extended emission from IRAS16342 but noted that it was patchy and could be attributed to Galactic cirrus contamination [55]. We detected dust emission at 70µm for all other objects in the survey (see section 3.2, above).

3.8.2 Data quality

The maps included in this thesis include the deepest, highest resolution far-IR maps of AGB shells ever made: the average sensitivity of the maps is 1.2 MJy sr$^{-1}$ (see table 3.1); and a pixel scale of 4''92 pixel$^{-1}$ was used to create most maps at 70µm. For comparison, the maximum entropy image reconstruction technique (HIRAS) applied to the IRAS 60µm and 100µm observations of AGB stars allowed a spatial resolution that approached the nominal diffraction limit of the telescope (1''0 at 60µm and 1''7 at 100µm) [30]. The spatial resolution of AKARI FIS greatly improved upon IRAS with a pixel scale of 26''8 pixel$^{-1}$ for N60 and WIDES-S (bands centered at 65µm and 90µm, respectively), and a pixel scale of 44''2 pixel$^{-1}$ for WIDE-L and N160 (bands centered at 140µm and 160µm, respectively) [34], but the spatial resolution of the Spitzer MIPS maps still exceeds AKARI FIS images. Recent Herschel far-IR maps were created using the PACS instrument with pixel scales of 5''6 and 11''3 at 70µm and 160µm, respectively [40]. The sensitivity of the Spitzer MLHES maps should be greater than Herschel maps because images of AGB objects observed with Herschel PACS at 70µm are expected to result in a sensitivity of $\sim$3 MJy sr$^{-1}$ (calculated using the estimated 1-σ point source sensitivity of 11.9 MJy sr$^{-1}$ at 70µm, a repetition factor of 8 and a signal gain of $\sqrt{2}$) compared to the Spitzer maps at $\sim$1.2 MJy sr$^{-1}$ included here.
3.8.3 Photometry

Dust shell flux estimates ranged from 3.2 Jy ± 0.2 Jy to 28.9 Jy ± 0.1 Jy. Estimated flux for each object is tabulated in Table 3.3. These values are a low estimate because of the data missing from the center of each map.

We attempted to recover missing data by fitting AKARI Bright Source Catalogue (BSC) data to our Spitzer 70µm data by assuming that the BSC data was of lower sensitivity and should represent the missing stellar contribution. For example, Izumiura et al. estimated the color corrected flux density for the extended shell of U Hya at 45.5 Jy ± 0.5 Jy, 43.4 Jy ± 0.2 Jy, 30.6 Jy ± 0.5 Jy and 23.0 Jy ± 1.5 Jy (65µm, 90µm, 140µm and 160µm, respectively) using AKARI FIS in slow scan mode [37]. They found an estimated point source contribution of 12.7 Jy ± 0.4 Jy and 5.4 Jy ± 0.1 Jy (65µm and 90µm, respectively) compared to the AKARI BSC lower sensitivity values of 9.90 Jy ± 1.16 Jy and 7.47 Jy ± 0.0884 Jy (65 µm and 90µm, respectively, with high quality). Assuming the star is a blackbody and the far-IR data is in the Rayleigh Jeans limit, one may estimate the AKARI BSC 70µm contribution at 9.5 Jy using a linear fit. We identified an optimum scaling factor of 0.023 for PRF subtraction for this source. We calculated 170 Jy as the total flux in a PRF map of combined Ceres and Red Rectangle data (a point source at 70 µm). Our estimate for the stellar contribution is 3.9 Jy, suggesting that AKARI BSC may have captured ~5.6 Jy flux from extended emission. Adding the AKARI BSC contribution to the Spitzer estimated flux of 28.9 Jy resulted in a total flux of 34.5 Jy. It does not appear that this technique recovers the total amount flux for this object as determined by Izumiura et al. because the estimated flux at 70µm is 45.1 Jy (determined using a power law fit to extended emission).
3.8.4 Dynamical age results

Dynamical age was calculated for dust shells exhibiting radial symmetry (15 of the total 34 sources). Dynamical ages were calculated to be on the order of \( \sim 1 \times 10^4 \) yr to \( \sim 4 \times 10^4 \) yr. The AGB is thought to last on the order of \( 10^6 \) yr. We would expect to find a few shells with dynamical age on the order of \( 10^5 \) yr. The missing ‘older’ shells are a puzzle.

One possible explanation is that dynamical age was calculated using the estimated radius of the shell and the average expansion velocity of the gas, generally determined by CO(1-0) emission (see table 3.2), and assuming that the gas and dust are coupled (see discussion, section 1.4). The radius of the shell was estimated using an observationally-determined cutoff above the standard deviation of the sky background for each image. The actual edge of the shell, the region where the shell and ISM mix, could not be determined exactly for most sources in the thesis, and so the dynamical age for each shell is an estimate. It is possible the the cutoff for the shell was systematically set too low or that the assumption of constant mass loss is incorrect. A slower mass loss rate would yield shells of greater dynamical age.

Two exceptions to the estimated cutoff issue are the shells for U Hya and R Cas, both of which exhibited a well-defined AGB wind-ISM interface and radial symmetry. Pile-up was shown to be a dominant characteristic contributing to the shell morphology of U Hya, and so the ‘dynamical age’ calculated for this shell is really the crossing time for the material eject from the star to reach the region where the momentum flux of the wind and ram pressure of the ISM are in equilibrium. Our calculations suggested that the crossing time is on order of a few \( 10^4 \) years. Wind-ISM interaction has been shown to contribute to the morphology of R Cas [6], and yet the shell exhibits radially symmetry, rather than ‘bow shock and tail’ structure suggested by wind-ISM models. The windward edge of the shell should be constrained by a contact discontinuity, as has been shown with other wind-ISM
interaction cases, such as R Hya [58]. In that case, at least for the windward edge, the ‘dynamical age’ of this shell is also a measure of the crossing time. Our calculations suggest that the crossing time for the R Cas shell is on the order of $10^4$ years. Interestingly, Wareing et al. discovered that their simulations of the dust shell surrounding R Hya reached a stable state in a few $10^4$ years, and so a crossing time estimate on this order is consistent with their results [60].

Another possible explanation for the youthful age of shells where the wind-ISM interaction is not dominant is that the density of material at the outer edges of a circumstellar shell of age $\sim 10^5$ yr might be too low to emit detectable surface brightness at 70$\mu$m, assuming the shell is in thermal equilibrium. Dynamical age was calculated only for shells that exhibited radial symmetry. Villaver et al. have shown that symmetric gas shells that even low densities or low relative velocities may contribute to the formation of bow shock-like or cometary structures [65]. Hence, our sample for dynamical age calculation suffers from a selection bias because dynamical age was calculated for those shells where the relative velocity was low. Further, Villaver et al. illustrated the density profile of a low initial mass (1 $M_\odot$) star after a few $10^5$ yr. The shell is characterized by a higher density core surrounded by a much lower density structure. A useful extension of this work would be to model the surface brightness profile of such an object to determine if the outer shell could be detectable at 70$\mu$m by a telescope such as *Spitzer*.

### 3.8.5 Mass estimate results

The amount of mass in a circumstellar shell may be estimated by multiplying the dynamical age of the shell and the mass-loss rate from the literature, assuming constant mass loss. This estimate may then be compared with mass estimated using the flux from the maps. We estimated the dynamical age for 15 sources and obtained mass-loss rates from CO observations for 13 of those sources. We assumed
a gas-to-dust ratio of 150 for silicates and 200 for carbon grains and multiplied the
dust mass estimates by the gas-to-dust ratio to find the mass of gas in the shell.
(The total mass is the sum of dust mass and gas mass, but the gas contribution
dominates the total mass estimate.) We then compared the mass of gas from the
dynamical age calculation to the mass estimated by multiplying the dust mass by
the adopted gas-to-dust ratio.

As expected, the missing surface brightness data from the center of the maps
resulted in a poor comparison between estimated mass from dynamical age and mass
calculated using flux from the maps. Dynamical age calculations resulted in a range
of mass values from $\sim 1 \times 10^{-3} \, M_{\odot}$ to $\sim 5 \times 10^{-2} \, M_{\odot}$. Estimates from the flux
calculation resulted in a range of mass values from $\sim 1 \times 10^{-4}$ to $\sim 1 \times 10^{-3}$, or
about an order of magnitude smaller. For individual objects, the flux calculation
recovered from $\sim 1\%$ to up to $\sim 30\%$ of the mass estimated from the dynamical age
of the shell.

It was possible to compare dust mass or mass-loss rate calculations for a few
objects observed by Spitzer at 70$\mu$m and by AKARI. For example, Ueta et al.
estimated the mass of dust in the circumstellar shell of R Cas as roughly $1 \times 10^{-5}$
$M_{\odot}$ to $5 \times 10^{-5} \, M_{\odot}$ using AKARI pointed observations [6]. Our estimate for this
source was $2.8 \times 10^{-6} \, M_{\odot}$ using the same distance and opacity. Our estimate of
dust mass is much lower because of missing data. A linear fit to the measured fluxes
at 65$\mu$m and 90$\mu$m (121.48 Jy and 73.42 Jy, respectively) suggested that AKARI
could have measured $\sim 89$ Jy at 70$\mu$m from thermal dust emission, assuming that
the stellar contribution is negligible at this wavelength. Our flux calculation from
the Spitzer map at 70$\mu$m was 17.4 Jy, or about 20% of the possible 70$\mu$m emission.
Using the estimated AKARI flux and a gas-to-dust ratio of 150 for silicates, we
found gas mass of $7 \times 10^{-3} \, M_{\odot}$, compared to a mass of $6 \times 10^{-3} \, M_{\odot}$ calculated
using dynamical age ($1.2 \times 10^4$ yr) and average mass loss rate from the literature
(5.2 \times 10^{-7}: \text{see table 3.2}), in good agreement with the total mass of $5 \times 10^{-3} \, M_\odot$ estimated by Ueta et al.

Arimatsu et al. used observations of U Ant by Herschel and AKARI to constrain inner shells of the carbon star U Ant identified as episodic in this thesis [36]. They identified one dust-poor inner shell and a second shell with dust mass $1.6 \times 10^{-5} \, M_\odot$ corresponding to the bright core of emission in our Spitzer map with dynamical age $\sim 3 \times 10^3 \, \text{yr}$. We identified an outer shell of dust mass $1.9 \times 10^{-6} \, M_\odot$ corresponding to a dynamical age of $1.2 \times 10^4 \, \text{yr}$ in our observations. We calculated a mass-loss rate of $1.1 \times 10^{-6} \, M_\odot$ for the inner shell using AKARI data in good agreement with the mass-loss rate of $1.4 \times 10^{-6} \, M_\odot \, \text{yr}^{-1}$ from the literature, but found a much lower mass-loss rate of $\sim 3 \times 10^{-8} \, M_\odot \, \text{yr}^{-1}$ for the outer shell.

3.8.6 Correlation between morphology and stellar characteristics

We identified no correlation between morphology and chemistry of the star. For example, the 14 objects identified as wind-ISM interaction included 9 oxygen-rich, 4 carbon stars and 1 S star. The 5 episodic morphologies included 3 oxygen-rich stars and 2 carbon stars. The 4 objects characterized by a regular morphology included 2 oxygen-rich stars and 2 carbon stars. The 2 elliptical morphologies included 1 oxygen-rich and an S star. Lastly, 1 carbon star was identified as pile-up morphology.

We could not determine space motion for 2 morphologies (RZ Sgr and KK Car) because the literature lacked radial velocity and/or proper motion data. The space motion ranged from 8.1 km s$^{-1}$ to 100.5 km s$^{-1}$ and averaged 43.4 km s$^{-1}$ for the 25 objects with identified morphologies presented in this thesis. We identified a correlation between regular morphology and space motion: objects with regular morphologies had less than average space motion. The space motion for these 4 objects ranged from the lowest space motion of the sample, 8.1 km s$^{-1}$ (Y Lyn), to
40.6 km s$^{-1}$ (V Tel). Y CVn, classified as regular, had the fifth lowest space motion (23.4 km s$^{-1}$). RT Cap had the tenth lowest (35.9 km s$^{-1}$).

Objects classified as ISM interaction had space motion that ranged from 19.7 km s$^{-1}$ (V Pav) to the largest space motion of the sample, 100.5 km s$^{-1}$ (X Pav). Interestingly, 4 objects with ISM interaction morphologies had above average space motion (R Cas, TX Psc, R Hya, RT Vir, in descending order), but 8 objects had below average space motion (EP Aqr, RV Cyg, U Men, SW Vir, RS Cnc, RS And, Y Hya and V Pav, also in descending order). We calculated the space motion of R Hya, a bow shock case, at just above average (47.4 km s$^{-1}$). Ueta et al. found a space velocity of $50 \pm 1$ km s$^{-1}$ for R Hya using Hipparcos proper motion in RA and Dec and the same distance and radial velocity that we adopted here [58]. R Cas showed evidence of dust grain heating from weak shocks, but not a characteristic bow shock and tail structure even though the space motion calculated is greater (72.5 km s$^{-1}$) than the space motion of R Hya [6]. Ueta et al. have shown that the relative flow between the ISM and the shell contributes to the formation of bow shock structure or collisional heating [58, 6]. It is the relative flow between the ISM and shell that contributes to the ISM interaction morphologies identified in this thesis, not just the size of the space motion of the star.
Table 3.1: Spitzer MIPS Observations of Evolved Stars

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2Variability type and period is from the General Catalog of Variable Stars (GCVS) Samus, et al. (2007-2010), except X TrA period is from Percy et al. (2009).

3Spectral type from Hipparcos except V Tel, V PsA, U Men, RZ Sgr, KK Car, RS And from Stellar Maser Observations Benson et al. (1990). X TrA spectral type from Hipparcos is N0v, SIMBAD is C and Samus et al. (2007-2010) is C5.5(NB).

4Proper motion in RA and Dec from Hipparcos, the New Reduction, van Leeuwen et al. (2007), except R Cas from Vlemmings et al. (2003), V PsA and NCG 6543 from Hipparcos; U Men, V Tel, RS And from The Tycho Catalog (Hog et al., 1998).

5Radial velocity from the General Catalog of mean radial velocities (Barbier-Brossat et al., 2000), except HD 161796 from Abt (1960); W Hya, Y Hya, \(\delta^2\) Lyr, U Hya and X TrA from the General Catalogue of Radial Velocities; RT Vir from Famaey et al. (2005); U Men from Feast et al. (2000); V Tel, V PsA and RS And from Feast et al. (1972).

6Weighted averages used when necessary for \(V_{\exp}\) except for KK Car, \(\delta^2\) Lyr, R Lyr estimated at 10.0 km s\(^{-1}\).

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1. Star centric coordinates were used to determine the radius of shell, except for EP Aqr where center of ellipse was used for radial profile.

2. Surface brightness given is lower limit.

3. Morphologies: (P) pile-up, ($\Delta$) episodic, (E) elliptical, (R) regular, (ISM) ISM interaction, (PSF) bright object
Table 3.4: Mass of Dust

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Figure 3.1: U Hya imaged at 70\,µm. North is up, east to left. The surface brightness is given by the false color scale to the right of the image. The location of the star is indicated by a star symbol and the direction of proper motion is marked by the yellow line. Note the tail of material trailing opposite the direction of proper motion. Below the image is a geocentric radial profile of average surface brightness by average distance for two regions: one centered on the tail emission for 30° to each side of PA 292° (heavy solid line) and the other containing the windward emission (solid line). The average is indicated by the dashed line. The emission peaks at \( \sim 109° \). The 2\,σ edge of the shell is at 162'' ± 4''. A model fit of constant mass loss is plotted for comparison (dot-dash line). The tail structure suggests that the AGB-wind ISM interaction defines the boundary of the shell and that pile-up is occurring at the edge of the shell.
Figure 3.2: W Hya imaged at 70 µm. North is up, east to left. The surface brightness is given by the false color scale to the right of the image. The location of the star is indicated by a star symbol and the direction of proper motion is marked by the yellow line. Below the image is a radial profile plot in log-log scale. A power law fit (dashed line) from ~72" to ~117" resulted in an $\alpha$ of 4.5 and delineates the region of enhanced surface brightness centered in the image. A second power law fit (solid line) from ~117" to ~230" resulted in an $\alpha$ of 0.4 and delineates the region of lower surface brightness surrounding the central bright core. We measured the 2σ edge of shell at 271"±8". A model fit of constant mass loss is plotted for comparison (dot-dash line). The slope deviations suggest that W Hya has experienced at least 2 epochs of mass loss.
Figure 3.3: R Lyr imaged at 70µm. North is up, east to left. The surface brightness is given by the false color scale to the right of the image. The location of the star is indicated by a star symbol and the direction of proper motion is marked by the yellow line. Below the image is a radial profile plot in log-log scale. A power law fit from the center of the image to an inflection point (dashed line) results in an $\alpha$ of 2.0. A second power law fit (solid line) from the inflection to $\sim 180''$ yielded an $\alpha$ of 1.7 in the region of lower surface brightness surrounding the center. The flattening of the log-log plot corresponds to a surface brightness enhancement. The 2σ edge of the shell is at $\sim 180''$. A model fit of constant mass loss is plotted for comparison (dot-dash line). The slope deviations suggest that R Lyr has experienced at least 2 epochs of mass loss. A first epoch of nearly constant mass loss was interrupted and followed by a second epoch of increasing mass loss.
Figure 3.4: U Ant imaged at 70\(\mu\)m. North is up, east to left. The surface brightness is given by the false color scale to the right of the image. The location of the star is indicated by a star symbol and the direction of proper motion is marked by the yellow line. Below the image is a radial profile plot in log-log scale. A power law fit (dashed line) from the center to an inflection point at \(\sim 75''\) resulted in an \(\alpha\) of 3.3 indicating a period of increasing mass loss. A second power law fit (solid line) from \(\sim 75''\) to \(\sim 158''\) resulted in an \(\alpha\) of 1.8. The 1.5\(\sigma\) edge of the shell is located at \(\sim 204''\). The linear portion of a model fit of constant mass loss constrained to the shell size is plotted for comparison (dot-dash line). The slope deviation suggests that U Ant has recently experienced a change to mass loss after an epoch of constant mass loss.
Figure 3.5: T Mic imaged at 70 µm. North is up, east to left. The surface brightness is given by the false color scale to the right of the image. The location of the star is indicated by a star symbol and the direction of proper motion is marked by the yellow line. There is bright central core of emission and extended faint emission to the south opposite the direction of proper motion. Below the image is a radial profile plot in log-log scale. The surface brightness distribution was fitted with a power law fit (dashed line) from the center of the map to \( \sim 70'' \) that resulted in an \( \alpha \) of 2.4 and a second power law fit from \( \sim 73'' \) to \( \sim 143'' \) that yielded an \( \alpha \) of 1.6. A model fit of constant mass loss is plotted for comparison (dot-dash line). The slope deviation suggests that T Mic has experienced a recent increase to mass loss after an epoch of nearly constant mass loss.
Figure 3.6: X TrA imaged at 70µm. North is up, east to left. The surface brightness is given by the false color scale to the right of the image. The location of the star is indicated by a star symbol and the direction of proper motion is marked by the yellow line. Notice the region of surface brightness enhancement north of the star. Below the image is a radial profile plot in log-log scale. A gaussian fit revealed a broad peak centered at $\sim 118''$ which corresponds in radial extent to the outer edge of the bright region north of the star. A power law fit (solid line) from an inflection point at $\sim 142''$ to the edge of shell at $\sim 186''$ resulted in an $\alpha$ of 1.9. A model fit of constant mass loss is plotted for comparison (dot-dash line). The slope change suggests that X TrA has experienced two epochs of mass loss. An early epoch of nearly constant mass loss was followed by an epoch of decreasing mass loss.
Figure 3.7: RZ Sgr imaged at 70\(\mu\)m. North is up, east to left. The surface brightness is given by the false color scale to the right of the image. The location of the star is indicated by a star symbol and the direction of proper motion is marked by the yellow line. The 70\(\mu\)m emission appears elongated northwest to southeast. We fit an ellipse to the surface brightness distribution (at 2\(\sigma\) sky background) and found a semi-major axis of 162″, semi-minor axis of 116″ and eccentricity of 0.70 at position angle of 155°. The 2\(\sigma\) edge of shell is estimated at 129″ \(\pm\) 3″.
Figure 3.8: V PsA imaged at 70µm. North is up, east to left. The surface brightness is given by the false color scale to the right of the image. The location of the star is indicated by a star symbol and the direction of proper motion is marked by the yellow line. The shell exhibits an elliptical morphology with elongation northwest to southeast. There is extended emission southeast of the star in the direction of proper motion. The 2σ edge of shell is estimated at 92″ ± 6″. This shell was categorized as elliptical because of its resemblance to the elliptical morphology exhibited by RZ Sgr.
Figure 3.9: Y CVn imaged at 70µm. North is up, east to left. The surface brightness is given by the false color scale to the right of the image. The location of the star is indicated by a star symbol and the direction of proper motion is marked by the yellow line. Below the image is a radial profile plot in log-log scale of average surface brightness (symbols) by average distance. A power law fit (dashed line) between the center and the edge of the shell resulted in an $\alpha$ of 0.5. The 1.4σ edge of shell is at $235'' \pm 1.5''$. A model of constant mass loss is plotted for comparison (dot-dash line). The slope deviation suggests that Y CVn has experienced one epoch of decreasing mass loss.
Figure 3.10: Y Lyn imaged at 70µm. North is up, east to left. The surface brightness is given by the false color scale to the right of the image. The location of the star is indicated by a star symbol and the direction of proper motion is marked by the yellow line. Below the image is a radial profile plot in log-log scale. The 1.5σ edge of the shell is at 145″ ± 8″. A power law fit from ~125″ to ~145″ (solid line) resulted in an α of 2.2. A model fit of constant mass loss is plotted for comparison (dot-dash line). The slope suggests that Y Lyn has experienced one epoch of mass loss. There is evidence that mass loss has decreased recently, but the data are noisy close to the star. Note two far-IR sources not related to the dust emission from this source: one to the northeast and one to the south from the star.
Figure 3.11: V Tel imaged at 70µm. North is up, east to left. The surface brightness is given by the false color scale to the right of the image. The location of the star is indicated by a star symbol and the direction of proper motion is marked by the yellow line. Two far-IR sources are evident in the image: a point source to the southeast and a larger source south of the star. Both were removed for photometry. Below the image is a radial profile plot in log-log scale. A power law fit (solid line) from \(\sim 125''\) to \(\sim 155''\) resulted in an \(\alpha\) of 1.2. The 1.2\(\sigma\) edge of shell is at 155'' \(\pm 8''\). A model fit of constant mass loss is plotted for comparison (dot-dash line). The slope suggests that V Tel has experienced one epoch of constant mass loss. There is evidence that mass loss has decreased recently, but the data are noisy close to the star.
Figure 3.12: RT Cap imaged at 70\(\mu\)m. North is up, east to left. The surface brightness is given by the false color scale to the right of the image. The location of the star is indicated by a star symbol and the direction of proper motion is marked by the yellow line. The dust emission is symmetric around the star but not uniform. Below the image is a radial profile plot in log-log scale. A power law fit from \(\sim 85''\) to \(\sim 105''\) (solid line) resulted in an \(\alpha\) of 1.2. A model fit of constant mass loss is plotted for comparison (dot-dash line). The slope suggests that RT Cap has experienced one epoch of constant mass loss. There is evidence that mass loss has decreased recently, but the missing data close to the star makes this region difficult to evaluate. The 1.5\(\sigma\) edge of shell is at 105'' \(\pm 6''\).
Figure 3.13: R Hya imaged at 70µm. North is up, east to left. The surface brightness is given by the false color scale to the right of the image. The location of the star is indicated by a star symbol and the direction of proper motion is marked by the yellow line. There is surface brightness enhancement to the west of the star that has been attributed to a bow shock [58].
Figure 3.14: RT Vir imaged at 70µm. North is up, east to left. The surface brightness is given by the false color scale to the right of the image. The location of the star is indicated by a star symbol and the direction of proper motion is marked by the yellow line. The map shows evidence of a parabolically-shaped density enhancement similar to bow shock structures found in other objects such as R Hya.
Figure 3.15: SW Vir imaged at 70µm. North is up, east to left. The surface brightness is given by the false color scale to the right of the image. The location of the star is indicated by a star symbol and the direction of proper motion is marked by the yellow line. Note the cometary shape to the dust emission.
Figure 3.16: Y Hya imaged at 70μm. North is up, east to left. The surface brightness is given by the false color scale to the right of the image. The location of the star is indicated by a star symbol and the direction of proper motion is marked by the yellow line. The map shows evidence of a parabolically-shaped density enhancement similar to bow shock structures found in other objects such as R Hya.
Figure 3.17: R Cas imaged at 70µm. North is up, east to left. The surface brightness is given by the false color scale to the right of the image. The location of the star is indicated by a star symbol and the direction of proper motion is marked by the yellow line. There is surface brightness enhancement to the east of the star toward the direction of proper motion and the emission to the west is faint. Ueta et al. attributed the surface brightness enhancement to an ISM flow local the star [6]. Below the image is a radial profile plot of average surface brightness by average distance for two regions: the enhanced region (circles) and the faint region (diamonds). The combined average is represented by the dashed line. The surface brightening to the east can be seen as enhanced emission in the radial plot. The average 2σ edge of shell is at 176" ± 4".
Figure 3.18: RS Cnc imaged at 70µm. North is up, east to left. The surface brightness is given by the false color scale to the right of the image. The location of the star is indicated by a star symbol and the direction of proper motion is marked by the yellow line. The surface brightness distribution is irregular with a large extension (∼235") to the northwest that appears ‘tail-like’. The trail of emission does not appear to be opposite the direction of proper motion in this case and there is no evidence of brightening near the star. The most likely explanation for a trail of material away from the star is an interaction with the ISM. The trail of emission in the far-IR is coincident with a similar trail observed in H\textsc{i} [100].
Figure 3.19: X Pav imaged at 70μm. North is up, east to left. The surface brightness is given by the false color scale to the right of the image. The location of the star is indicated by a star symbol and the direction of proper motion is marked by the yellow line. The dust emission is enhanced to the east of the star in the direction of proper motion and there is a trail of emission to the west opposite to the direction of proper motion. There is evidence that an ISM interaction may be contributing to brightening, as has been shown in the case of R Cas.
Figure 3.20: EP Aqr imaged at 70\(\mu\)m. North is up, east to left. The surface brightness is given by the false color scale to the right of the image. The location of the star is indicated by a star symbol and the direction of proper motion is marked by the yellow line. The 70\(\mu\)m emission appears elongated northwest to southeast and is brighter to the south of the star. The shape of the morphology is similar to the ‘tear-drop’ shape of the emission from X Pav and suggests an ISM interaction.
Figure 3.21: V Pav imaged at 70µm. North is up, east to left. The surface brightness is given by the false color scale to the right of the image. The location of the star is indicated by a star symbol and the direction of proper motion is marked by the yellow line. The surface brightness distribution appears to have a ‘tear-drop’ shape similar to X Pav which may indicate the parabolic shape and trail of emission from an ISM interaction.
Figure 3.22: RV Cyg imaged at 70µm. North is up, east to left. The surface brightness is given by the false color scale to the right of the image. The location of the star is indicated by a star symbol and the direction of proper motion is marked by the yellow line. There is surface brightness enhancement to the north, and possibly the south, of the star and very little emission to the west of the star in the direction of proper motion. An ISM interaction may be contributing to brightening close to the star and there may be a trail of emission in the direction opposite the direction of proper motion as has been shown in the far-IR and H I for RS Cnc.
Figure 3.23: TX Psc imaged at 70\(\mu\)m. North is up, east to left. The surface brightness is given by the false color scale to the right of the image. The location of the star is indicated by a star symbol and the direction of proper motion is marked by the yellow line. There is enhanced emission to the north of the star and a trail of material to the west opposite the direction of proper motion. An ISM interaction appears to be stripping material off the shell to create a trail of emission as has been shown in the far-IR and and H\(\text{I}\) for RS Cnc.
Figure 3.24: KK Car imaged at 70µm. North is up, east to left. The surface brightness is given by the false color scale to the right of the image. The location of the star is indicated by a star symbol and the direction of proper motion is marked by the yellow line. Enhanced surface brightness extends to the west opposite the direction of proper motion. The enhanced emission appears similar to the ‘tail-like’ emission from RS Cnc. The most likely explanation for a trail of emission is interaction with the ISM.
Figure 3.25: U Men imaged at 70μm. North is up, east to left. The surface brightness is given by the false color scale to the right of the image. The location of the star is indicated by a star symbol and the direction of proper motion is marked by the yellow line. There is a trail of material to the northwest similar to “tail-like” structures in other objects, such as RS Cnc.
Figure 3.26: RS And imaged at 70µm. North is up, east to left. The surface brightness is given by the false color scale to the right of the image. The location of the star is indicated by a star symbol and the direction of proper motion is marked by the yellow line. The surface brightness distribution is irregular and not uniform. There is extended emission northwest of the star opposite the direction of proper motion and very little emission in the direction of proper motion. We classified the morphology as ISM interaction because the surface brightness distribution is offset from the star.
Chapter 4

Conclusions

A study of twenty-seven observed circumstellar dust shells revealed five different types of morphologies which were characterized by the appearance of the surface brightness distribution and the presence or absence of changes to mass loss. Each category described the underlying process that played a dominant role in shaping the morphology. The five categories identified were: Pile-Up, Episodic, Elliptical, Regular and ISM Interaction. We identified five compelling cases of sources that demonstrated evidence of changes to mass loss history. We found little correlation with morphology and stellar characteristics; notably, there appeared to be no correlation with changes to mass loss and chemistry of the star. Finally, we determined that constant mass loss may be a poor assumption when modeling circumstellar dust shells because we compared a surface brightness model of constant mass loss to 11 sources with spherical symmetry and identified no good fits.

Pile-up was a major contributor to shaping the circumstellar dust shell of U Hya, a carbon star. In addition to pile-up, the shell of U Hya showed evidence that the wind-ISM interaction also contributed to the morphology by stripping material from the shell. Pile-up was an important contributor to shell structure because any mass loss history greater than the crossing time of the shell was lost due to the material
piling up at the edge of the shell. For example, in the case of U Hya, any episodic events prior to a few $10^4$ years ago were not visible in the shell because this material had already piled up at the edge.

Five objects exhibited evidence that a change had occurred during the mass loss history of the shell: R Lyr, W Hya and T Mic, oxygen-rich stars; and U Ant and X TrA, both carbon stars. The morphologies of shells included in this category were generally symmetric and often exhibited a bright central core surrounded by faint emission. Two distinct epochs of mass loss were evident in each of these shells, with enhanced emission generally occurring most recently. The presence or absence of technetium did not correlate with episodic mass loss events because it has been shown that the $^{99}$Tc absorption line is probably not present in the spectrum of R Lyr, is possibly present in the spectrum of T Mic and is probably present in the spectrum of W Hya [82]. Interestingly, the dynamical age of the shell was not a good indicator of which objects would exhibit changes to mass loss. The shell of R Lyr strongly exhibited evidence of a change to mass loss, and yet the dynamical age of the shell was young, $0.8 \times 10^4$ yr (assuming the preferred distance and expansion velocity), compared to other observed sources. The two shells of greatest dynamical age (or crossing time) surrounded X Pav and Y CVn, ($4.1 \times 10^4$ yr and $4.4 \times 10^4$ yr, respectively) and neither shell showed evidence of changes to mass loss in the history of the shell within the timescale of the observations.

Two objects exhibited morphologies that could be characterized as elliptical: RZ Sgr, an S star; and V PsA, an oxygen-rich star. The surface brightness distribution appeared elongated along one axis in each of these shells. The elliptical shape could be evidence for axisymmetric mass loss. The case for axisymmetric mass loss was greatest for RZ Sgr because the shape of the shell could be well-defined by an ellipse and the center of the elliptically-shaped emission was approximately coincident with the star.
The dominant characteristic of circumstellar dust shells surrounding Y Lyn and V Tel, both oxygen-rich stars; and Y CVn and T Mic, both carbon stars, was that the shells appeared regular. The shells were largely symmetric with no evidence of pile-up or a change to mass loss within the timescale of the observations. There were no obvious indications that the ISM flow local to the star had contributed to shaping the morphology of the shell. For example, there were no extensions to suggest that material was being stripped from the shell, regions of enhanced surface brightness to suggest collisional heating, or parabolic arcs to suggest the presence of bow shock structure.

ISM interaction contributed significantly to shaping the shell morphology of 14 objects included in this thesis study. The degree of interaction varied among the objects. For example, R Hya, an oxygen-rich star, has been shown to exhibit bow shock structure. The surface brightness distribution surrounding SW Vir and RT Vir, both oxygen-rich stars; and Y Hya, a carbon star, exhibited evidence of a concentric arc that is a parabolically-shaped density enhancement also suggestive of bow shock structure. Weak shock from an AGB wind-ISM collisional interaction has been shown to contribute to dust temperature enhancement in the shell of R Cas.

The most likely explanation for a trail of emission or tail-like structure is that material is being displaced by the relative motion of the ISM flow local to the star. RS Cnc, an S star, is thought to exhibit ISM interaction in both the far-IR and in H\textsubscript{I} emission [100]. The surface brightness distribution surrounding X Pav and EP Aqr, both oxygen-rich stars; and V Pav, a carbon star showed evidence of a ‘tear-drop’ shape that could be the head and tail of a bow shock. X Pav also showed evidence of brightening. RV Cyg and TX Psc, both carbon stars, exhibited brightening near the star and evidence of a trail of emission away from the star. A dust temperature enhancement could be present in these shells, or the surface brightness enhancement could be attributed to a density enhancement near the star. The surface brightness
distribution surrounding RS And was noticeably offset from the star. Finally, two sources exhibited extended emission that appeared to be a trail of emission away from the star; however, these shells did not exhibit evidence of brightening: KK Car and U Men, both oxygen-rich stars. Turbulent tails have been shown in models of bow shock structures, and so objects exhibiting tail-like structures were included in the ISM interaction category.

The most compelling conclusion from this work is that roughly half of the objects with extended emission showed some interaction between the AGB wind and the ISM flow local to the star. Further, the space motion of the star did not correlate well with the degree of interaction because some stars with below average space motion ($v_\ast < 43.4$ km s$^{-1}$) exhibited shells with ISM-interaction morphologies. This thesis demonstrated that in addition to observing mass loss history, far-IR investigations can reveal much about the AGB wind-ISM interaction. Extending models of wind-ISM interaction to include interactions with low relative velocities would contribute greatly to our understanding of how low relative flows contribute to shaping dust shell morphologies.

4.1 Next Steps

The most important next step in this work is to characterize the ISM flow local to the star for those sources which exhibit ISM-interaction morphologies. This study would help define previously unknown characteristics of the ISM. In addition, a more rigorous application of radiative transfer models and a more thorough investigation to recover missing flux data could improve the dust mass estimates presented in this thesis. A more accurate estimate of dust mass in the shell would help constrain the gas-to-dust ratio used in estimating total mass loss. For episodic shells, a more accurate dust mass estimate may better constrain mass loss rates for various epochs. Mass loss rates are used in simulations that include dust in modeling mass loss
history. Finally, another next step that could prove fruitful would be to consider data across wavelengths when such data are available. For example, useful Spitzer data may exist in the archives for some objects included in this thesis. Ueta et al. have shown that dust temperature and optical depth maps are a useful tool for investigating the nature of wind-ISM interactions [6].
Bibliography


sequence of helium shell flashes?,” *Astronomy and Astrophysics* (ISSN 0004-6361), vol. 230, p. L13, Apr 1990.


[66] C. J. Wareing, A. A. Zijlstra, and T. J. O’Brien, “The interaction of planetary nebulae and their asymptotic giant branch progenitors with the inter-


Appendices
Appendix A IDL Programs

Data reduction was performed using the IDL program ‘timeseq_hnp.pro’. This program was designed to read MIPS 70μm bcd files, perform background subtraction and write background-subtracted bcd files to a new directory. A mosaic was then created using MOPEX software and the background-subtracted bcd files. See section 2.3 Data reduction techniques for more information about background subtraction and mosaicking.
pro timeseq_lnp, arcsec, outflag, perflag, skyflag, med, SILENT = silent

; USAGE: timeseq_lnp, 320, 1, 0, 0, 0
; EXECUTE:
; The program asks the user to identify the input directory.
; Use the dialog box to select the full path ending with ../ch2/
; The program will build subdirectories: "lnp" to house background subtracted BCDs and "time_seq" to house the time series data for each pixel.
; All directory navigation is processed by the program after the input directory is selected.
;
; DESCRIPTION:
; Given MIPS data,
; look at data at each pixel as a time series and attempts to fit "sky" using linear fit first and then Fourier fit with Lomb-Scargle Periodogram
;
; INPUTS
; arcsec
; distance from star center: 250 - 350 arcseconds best
; outflag
; 0 - no output (test run)
; 1 - write sky subtracted BCD files
; perflag
; 0 - do not write time series for independent periodogram fitting
; 1 - write time series for Period04 processing
; skyflag
; 0 - do not write out one sky fits file per BCD for mosaicking
; 1 - write out sky files to mosaic
; Keyword /SILENT suppresses BCD level outputs to console
;
; OUTPUTS:
; med
; median sky background only when outflag set to 1
; x-direction: pixel/spatial dimension
; y-direction: temporal dimension
;
; PLOT legend
; Plot the valid data points in the dataset by pixel location over time
; Overplot error bars
; Overplot in blue those pixels that are part of the shell and are not part of background processing
; Overplot median and initial limits high and low as dashed lines

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; Overplot in red those readings outside of
cutoff (sigma clipped)
; Overplot a triangle on those pixels that pass
the second baseline fitting
; Overplot a dashed line for the linear fit

; PERIODOGRAM TEST file contains following data
; x, y, frequency, significance, Nyquist frequency

; VERSION: 1.8

; REVISIONS:
; 1.2 Lower threshold does not go below zero
; 1.3 Omit frequencies greater than Nyquist frequency (Rescinded)
; 1.4 Rename output datasets using i,j index
; 1.5 Add Period04 timeseries output
; 1.6 Add Julian date to time series output
; 1.7 Add user defined input directory; LNP HIFAC = 1
; 1.8 Include 160-micron data
; 12/3/10 Added IDL Journal file and stddev of sky
; 3/3/11 Added sky files for mosaicking

; Initialize

; FAP         = 0.05           ; Lomb false-alarm probability
upsig       = 1.0D           ; Set upper threshold to this sigma
lowsig      = 3.0D           ; Set lower threshold to this sigma
upsig2      = 1.0D           ; Second pass upper threshold
lowsig2     = 3.0D           ; Second pass lower threshold
infile      = '*_bcd.fits'   ; file and directories
infile2     = '*_bunc.fits'

; Plotting
psblack     = 0.           ; Postscript plotting colors
psred       = 1.
psgreen     = 2.
psblue      = 3.
xbblack     = 0            ;xwindow plotting colors
xred        = 255
xgreen      = 0
xblue       = 0

; Passed to calling routines
med         = 0.0D
jmax        = 0.0D          ; Periodogram processing
maxpeak     = 0.0D
sigvalue    = 0.0D
dev1        = 0.0D          ; Absolute deviation from ladfit
dev2        = 0.0D          ; Absolute deviation from second ladfit

; Flags
mflag       = 0           ; Pixel has high bmask value
lnpsigflag  = 0           ; Significant freq discovered

; Counters
totpix = 0L ; Pixels processed
pxreject = 0L
pxkeep = 0L
stimctr = 0L
nonstim = 0L
lnpsigctr = 0
lnpinsigctr = 0
lnpskipctr = 0
lnperrctr = 0
lnpfitctr = 0
lnpctr = 0
kresult = 0
NANctr = 0L
badctr = 0L ; count of bmask pixel array
offctr = 0L ;
on1ctr = 0L ; count of on1 array size
onctr = 0L ; count of on array size
shellctr = 0L ; count of shell array size
bkgrdctr = 0L ; count background pixels
mcount = 0L ; Count of bad bmask pixels
pass1ctr = 0L ; Count the number of times first pass skipped
pass2ctr = 0L ; Count numbe of times second pass skipped
invalidctr = 0L ; Count invalid thresholds
; Periodogram
Fc = 0.0D ; Nyquist frequency for time series
Fc_data = 0.0D ; Nyquist frequency for the dataset
Fflow = 0.0D ; Lowest frequency
Num = 0L
T = 0.0D
z = 0.0D
; Directory
master = '. '
pathname = DIALOG_PICKFILE(/DIRECTORY) ; root directory is master make two output directories here

if N_params() LT 5 then begin
print, 'Warning: supply input parameters!' print, 'Substituting default values'
arcsec = 320 ; background annulus
outflag = 1 ; set to 1 to write data files
perflag = 0 ; set to 1 to write periodogram test files
skyflag = 1 ; set to 1 to write out sky bcds
med = 0.0D
endif
begin_time = systime(1, /seconds)
silent = KEYWORD_SET(SILENT)
pathname = DIALOG_PICKFILE(/DIRECTORY)
; root directory is master make two output directories here
master    = pathname
        cd, master
;
If (outflag eq 0) and (perflag eq 0) and (skyflag eq 0) then begin
; No files are written but the sky emission is calculated
        JOURNAL, 'IDL_Log_Sky.txt'
Endif else begin
        JOURNAL, 'IDL_Log_lnp.txt'
Endelse
;
IF (outflag eq 1) then FILE_MKDIR, lnpdir
IF (perflag eq 1) then FILE_MKDIR, timeser
bcdpath   = pathname + bcddir
timepath  = pathname + timeser
lnppath   = pathname + lnpdir
; Change to BCD directory to read fits files
CD, bcdpath
filelist  = file_search(infile) ; set the input filelist
filelist2 = file_search(infile2)
s        = size(filelist)
nfiles   = s[1]             ; set the number of input files
img       = readfits(filelist[0],head)     ; first file in the list
source    = FXPAR(head, 'OBJECT')          ; source object
 timing0   = double(FXPAR(head,'SCLK_OBS')) ; time at the first read
 sstitle   = 'Source: ' + source         ; for plotting
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
; Define input arrays based on the data format
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

simg   = size(img)
y1     = simg[1]               ; input image x-dimension size
y2     = simg[2]               ; input image y-dimension size
pixdim = y1*y2
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
; Check data type
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
dtype = 1 if M1 ( 24um): 128x128 array
;  2 if M2 ( 70um):   16x32 array (only good side)
;  3 if M3 (160um):    2x20 array
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
dtype = long(FXPAR(head,'CHNLNUM'))
CASE dtype OF
  2: hstim = 'STMFL_70'
  3: hstim = 'STMFL160'
ELSE: STOP, 'Invalid file type', dtype
ENDCASE
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
; Define arrays
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
indata  = replicate(0.0D, y1, y2, nfiles)
inmask  = indata
inbkgrd = replicate(0, y1, y2, nfiles)
mask1   = replicate(0, y1, y2, nfiles)
timing  = replicate(0.0D, nfiles)       ; elapsed time only
julian = replicate(0.0D, nfiles) ; full Julian date
offstim = replicate(0, nfiles) ; input offstim flag array

; Line fit arrays
intercept = replicate(0.0D, y1, y2)
slope = replicate(0.0D, y1, y2)
corr1 = replicate(0.0D, y1, y2)
corr2 = replicate(0.0D, y1, y2)
intercepterr = replicate(0.0D, y1, y2)
slopeerr = replicate(0.0D, y1, y2)

; Periodogram fit array
freqdata = replicate({freqarr, ix:0, jx:0, freq:0.0D, $
                      signif:0.0D, Nyquist:0.0D}, pixdim)

; Output arrays
sub = replicate(0.0D, y1, y2)
sky = replicate(0.0D, y1, y2)
count = replicate(0.0D, y1, y2)
incle = replicate(1, y1, y2)

; Set plot device
!P.MULTI = 0
Set_plot, 'x'

if (dtype eq 2) then begin ; fix y1 to the working array dim
    oldy1 = y1
    y1 = 16
endif

for i=0,nfiles-1 do begin
    ; Make sure to be in BCD directory before reading fits files
    CD, bcdpath
    tmp = readfits(filelist[i], head, /SILENT, /NOSCALE)
stim = float(FXPAR(head,hstim)) ; if stim this is non-zero
    process nonstim BCD
    if (stim eq 0.) then begin
        ; Determine time stamp
        timing[nonstim] = double(FXPAR(head,'SCLK_OBS')) - timing0
        julian[nonstim] = double(FXPAR(head,'UTCS_OBS'))
        ; Build data array
        indata[*,*,nonstim] = tmp
        ; Build uncertainty array
        func = string(strjoin(strsplit(filelist[i],'bcd.fits', $
                        /EXTRACT,/REGEX),'bunc.fits'))
        tmp = readfits(func,uhead,/NOSCALE,/SILENT)
        insigma[*,*,nonstim] = tmp
        ; Build mask array
        fmask = string(strjoin(strsplit(filelist[i],'bcd.fits', $
                        /EXTRACT,/REGEX),'bmask.fits'))
        tmp1 = readfits(fmask,mhead,/NO_UNSIGNED,/SILENT)
inmask[*,*,nonstim] = tmp1
    offstim[i] = 1
    cd, lnppath

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BCD level processing identifies pixels too close to the star to be used for background sky calculation.

Creates a mask of background pixels for later use.

Call gcirc to determine distance of center of BCD to star

ra_ref = RA for the source star

dec_ref = Dec for the source star

arcsec_limit = user defined limit for background

ra_ref_rad = (ra_ref/180.0D) * !DPI ; Convert to radians
dec_ref_rad = (dec_ref/180.0D) * !DPI ; Convert to radians

crval1 = double(FXPAR(head,'CRVAL1'))
crval2 = double(FXPAR(head,'CRVAL2'))

if not silent then begin
    print, 'BCD: ', strcompress(string(i+1)),
        ' RA: ', strcompress(string(crval1)),
        ' Dec: ', strcompress(string(crval2)),
        ' Distance: ', strcompress(string(dis))
endif

Read through all the pixels and calculate distance to star

for n = 0, y1-1 do begin
    for m = 0, y2-1 do begin
        totpix = totpix + 1 ; Count pixels processed
        cx = DOUBLE(n)
cy = DOUBLE(m)
        ; Calculate RA and Dec for pixel
        xyad, head, cx,cy,a,d, /Celestial
        a_rad = (a/180.0D) * !DPI
d_rad = (d/180.0D) * !DPI
        ; Calculate distance using Barbieri 3.17
        ; All angles in radians
        RAdiff = ABS(ra_ref_rad - a_rad)
        CosA = SIN(d_rad)*SIN(dec_ref_rad) + $
            COS(d_rad)*COS(dec_ref_rad)*COS(RAdiff)
        dist_rad = ACOS(CosA)
        ; Convert to degrees
        distance = (dist_rad/!DPI) * 180.0D
        ; Convert to arcseconds
        distance = distance * 3600.0D
        if distance gt arcsec_limit then begin
            this is a valid pixel
            pxkeep = pxkeep + 1
            ; Set background mask to 1
\[
\text{inbkgrd}[n, m, \text{nonstim}] = 1
\]
endif else begin
; this pixel is on source
pxreject = pxreject + 1
endelse
endfor
endfor
nonstim = nonstim + 1 ; Count nonstim BCDs
endif else begin
stimctr = stimctr + 1 ; Count stim BCD
endelse
endfor
; reset the y1 value to include the entire array
if (dtype eq 2) then begin
y1 = oldy1
endif
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
; Set up timing array
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
\text{xdef} = \text{timing}[0:nonstim-1] ; build an array of timing data
\text{xjul} = \text{julian}[0:nonstim-1]
\text{num} = \text{indgen}(\text{nonstim})+1
;
\text{ymin} = \max(\min(\text{indata}[*,*,0:nonstim-1])*0.1,0) ; for plotting
\text{ymax} = \max(\text{indata}[*,*,0:nonstim-1])*0.3
;
\text{xmin} = \min(\text{xdef}) ; find minimum time for plotting
\text{xmax} = \max(\text{xdef}) ; find maximum time for plotting
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
; Calculate estimated Nyquist Frequency for the dataset
; See Numerical Recipes 13.8.9
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
\text{xdefmax} = \max(\text{xdef})
\text{xdefmin} = \min(\text{xdef})
\text{T} = (\text{xdefmax} - \text{xdefmin}) ; span of the input data
\text{M} = \text{N\_ELEMENTS(}\text{xdef})
\text{If} \text{\_T} \text{gt} 0 \text{then begin}
\text{FLow} = 1/\text{T} ; Lowest frequency
\text{Fc\_data} = \text{M}/(2.0D*\text{T}) ; Est Nyquist frequency for the dataset
endif else begin
\text{print}, 'Invalid period: ', \text{T}
\text{T} = 1.0D
\text{FLow} = 1.0D
\text{Fc\_data} = 1.0D
endelse
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
; Pixel level processing
; y1 equals 32 or the entire array for 70-micron data
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
for n=0,y1*y2-1 do begin
\text{cd, lnppath}
i = n \text{ mod y1} ; x-index
j = \text{floor(n / y1)} ; y-index
; if ((dtype eq 2) and (i lt 16)) OR $ ;
   if ((dtype eq 3) and (j ne 1)) then begin
if ((dtype eq 2) and (i lt 16)) OR $ (dtype eq 3) then begin
   ; process good part of array

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
; Set up postscript plotting for select pixel time series
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
stri = String(i)
strj = String(j)
strr = String(arcsec)
stri = strsplit(stri, ' ', /EXTRACT)
strj = strsplit(strj, ' ', /EXTRACT)
strr = strsplit(strr, ' ', /EXTRACT)
strij = stri+'_'+strj
IF (j eq 2*i) and (outflag eq 1) then begin
   Set_plot, 'ps'
   Device, FILENAME='Pixel_'+strij+'_'+strr+'.ps', $ /PORTRAIT, $ /ENCAPSULATED, /BOLD, /COLOR
   TVLCT, [0,255,0,0], [0,0,255,0], [0,0,0,255]
   red   = psred
   green = psgreen
   blue  = psblue
ENDIF

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
; Reorder the arrays by time series
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
y     = transpose(indata[i,j,0:nonstim-1])
yall  = y
sigy  = transpose(insigma[i,j,0:nonstim-1])
mask  = transpose(inmask[i,j,0:nonstim-1])
mmask = transpose(mask1[i,j,0:nonstim-1])
bkgrd = transpose(inbkgrd[i,j,0:nonstim-1])
; Eliminate pixels whose mask values indicate bad pixel
; See MIPS Users Handbook for list of values
; These are bmask values
for k=0,nonstim-1 do begin
   ; Count NAN pixels
   kresult = finite(y[k], /NAN)
   if kresult eq 1 then NANctr = NANctr + 1
   ; mask processing
   val    = mask[k]
   mflag  = 0
   if (val ge long(2.^15)) then begin
      val = val - long(2.^15)
   endif
   if (val ge long(2.^14)) then begin
      val = val - long(2.^14)
   mflag = 1
   endif
   if (val ge long(2.^13)) then begin
      val = val - long(2.^13)
mflag = 1
endif
if (val ge long(2.^12)) then begin
    val = val - long(2.^12)
mflag = 1
endif
if (val ge long(2.^11)) then begin
    val = val - long(2.^11)
mflag = 1
endif
if mflag eq 1 then begin
    ; count bad pixels and set mask
    mcount = mcount + 1
    mmask[k] = 1
endif
endfor
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;; Begin Linear fit
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
; calculate median and standard deviation of dataset,
; set thresholds
med = median(y, /EVEN)
sigymed = abs(stddev(y, /NAN, /DOUBLE))
upper = med + upsig * sigymed
lower = max([med - lowsig * sigymed, 0.0d]) ; lower threshold
    ; must be gt zero

; Test for thresholds calculated wih NAN values in the dataset
IF ((finite(upper, /NAN) eq 1) or $ (finite(lower, /NAN) eq 1)) then begin
    invalidctr = invalidctr + 1
endif
; Create arrays of indices
; on1 contains all values that are not NAN and are not
; rejected by bmask
; shell identifies pixels that are part of the shell
; on are the valid pixels that will undergo further
; processing
on1 = where(finite(y) and (mmask eq 0), on1ctr)
bad = where(finite(y) and (mmask eq 1), badctr)
off = where(finite(y) and ((y gt upper) or $ (y lt lower)), offctr )
shell = where(finite(y) and (mmask eq 0) and $ (bkgrd eq 0), shellctr)
on = where(finite(y) and (y le upper) and (y ge lower) $ and (mmask eq 0) and (bkgrd eq 1), onctr)
back = where(finite(y) and (y le upper) and (y ge lower) $ and (mmask eq 0) and (bkgrd eq 1), bctr)

; Plot the valid data points in the dataset by pixel
; location over time
; Overplot error bars
; Overplot in blue those pixels that are part of the shell
; Test to make sure the pixels exist before plotting
if on1ctr ne 0 then begin
    ypmax = max(y[on1])*1.1
ypmin = min(y[on1])
plot, xdef[on1], y[on1], PSYM=1, YRANGE=[lower, ypmax], XRANGE=[xmin, xmax], XSTYLE=1, YSTYLE=1,
title = 'Time Series: Linear and Periodogram Fit', subtitle = sstitle, xtitle = 'Time (sec)', ytitle = 'Brightness (MJky/sr)'
oploterr, xdef[on1], y[on1], sigy[on1] ; overplot median and initial limits
oplot, xdef, replicate(med,N_ELEMENTS(xdef)), LINESTYLE=1
oplot, xdef, replicate(upper,N_ELEMENTS(xdef)), LINESTYLE=1
oplot, xdef, replicate(lower,N_ELEMENTS(xdef)), LINESTYLE=1
endif
if shellctr ne 0 then begin
  oplot, xdef[shell], y[shell], PSYM=6, color=blue
endif
if offctr ne 0 then begin
  oplot, xdef[off], y[off], PSYM=1, color=red
endif
if badctr ne 0 then begin
  print, 'Bad pixels skipped'
endif
; Perform a basic line fit to the data if there are enough pixels
IF (N_ELEMENTS(on) ge 3) then begin
  result = ladfit(xdef[on], y[on], ABSDEV = dev1, /DOUBLE)
yfit   = result[0] + result[1] * xdef ;for plotting
xy_corr1    = correlate(xdef[on], y[on])
corr1[i,j]  = xy_corr1
intercept[i,j] = result[0]
slope[i,j]     = result[1]
if ((i eq 1) and (j eq 0)) then begin
  print, 'intercept (1, 0): ', result[0]
  print, 'slope (1, 0)    : ', result[1]
endif
; Calculate median and standard deviation
med     = median(y, /EVEN)
sigymed = abs(stddev(y, /NAN, /DOUBLE)) ; set new upper and lower thresholds
upper   = med + upsig2 * sigymed
lower   = max([med-lowsig2 * sigymed, 0.0d])
; choose a new set of pixels that make the second pass
on = where(finite(y) and (y ge lower) and (y le upper) and (mmask eq 0) and (bkgrd eq 1), onctr)
; plot the line fit over the plot of pixel values
oplot, xdef, yfit, LINESTYLE=2
endif else begin
  pass1ctr = pass1ctr + 1
  intercept[i, j] = 0
  slope[i, j]     = 0
  print, "Invalid i, j", i, j
endelse
; Verify there are at least 3 data points for second line fit
if (n_elements(on) ge 3) then begin
  ; perform a second line fit
  result = ladfit(xdef[on], y[on], /DOUBLE, ABSDEV = dev2)
  yfit2 = result[0] + result[1] * xdef
  xy_corr2 = correlate(xdef[on], y[on])
  ; calculate the slope and intercept from the
  ; second pass data
  intercept[i,j] = result[0]
  slope[i,j] = result[1]
  corr2[i,j] = xy_corr2
  ; overplot a triangle on those pixels that
  ; pass the second baseline fitting
  oplot, xdef[on], y[on], PSYM=5, color=green
  oplot, xdef, yfit2, linestyle=5, color=green
endif else begin
  pass2ctr = pass2ctr + 1
endelse
endelse
; Fit the line to all pixels
y = y - (intercept[i,j] + (slope[i,j]*xdef))
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
; Perform a LNP periodogram fit to the data if there are
; enough pixels
; Reset values and indicators before beginning
; wk1 contains a vector of frequencies
; wk2 contains the power value for the frequency in wk1
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
; See Numerical Recipes (13.8.9) for details
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
; Start by recalculating the Nyquist frequency for this pixel's
; time series. The time series is different for each pixel because
; the range of valid brightness values varies for each pixel
; Write time series to file for further processing if user flag set
; Verify there are background values in the time series first
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
If bctr ne 0 then begin ; Background values exist
  xback = xdef[back]
  xback = max(xback)
  xmin = min(xback)
  T = (xback - xmin) ; span of the input data
  Numb = N_ELEMENTS(back)
If T gt 0 then begin
  FLow = 1/T ; Lowest frequency
  Fc = Numb/(2.0D*T) ; Estimated Nyquist frequency
endif else begin
  print, 'Invalid period: ', T
  T = 1.0D
  FLow = 1.0D
  Fc = 1.0D
endelse
; If ((Numb gt 0) and (FAP gt 0)) then begin
; Power for significance plotting
z = - ALOG(FAP/Numb)
endif else begin
  print, 'ERROR - Number of background elements zero'
endelse

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

; Write file of surface brightness and timing for further
; processing with Periodogram fit program Period04
; back contains every valid background data point
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
if (perflag eq 1) then begin
  CD, timepath, CURRENT=master
  iter = bctr
  FILESTRING='Series_'+strij+'.dat'
  GET_LUN, Unit
  OPENW, Unit, FILESTRING
  fidx = 0
  WHILE (fidx LT iter) do begin
    printf, Unit, xjul[back[fidx]], xdef[back[fidx]], $y[back[fidx]]
    fidx = fidx+1
  ENDWHILE
  CLOSE, Unit
  FREE_LUN, Unit
  CD, master
endif
endif

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
; Periodogram fit
; Reset variables before beginning
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

jmax = 0.0D
maxpeak = 0.0D
sigvalue = 0.0D
lnpsigflg = 0
result2 = [0.0D, 0.0D]
IF (N_ELEMENTS(back) ge 20) then begin
  lnpctr = lnpctr + 1
  ; perform a lomb periodogram analysis
  result2 = LNP_TEST(xdef[back], y[back], /DOUBLE, $OFAC = 4, HIFAC = 1, $WK1 = wk1, WK2 = wk2, JMAX = jmax)
  maxpeak = result2[0]
  sigvalue = result2[1]
  if (sigvalue le FAP) then begin
    If not silent then begin
      print, 'i,j ', i, j
      print, 'Frequency & significance: ', wk1[jmax], $sigvalue
      print, 'Estimated Nyquist frequency: ', Fc
    endif
  freqdata[n] = {freqarr, i, j, wk1[jmax], sigvalue, Fc}
  lnpsigflg = 1
  lnpsigctr = lnpsigctr + 1
endif
Check for frequencies greater than the Nyquist frequency
These frequencies are valid because ambiguity is removed from
any aliasing for randomly sampled data.
See Numerical Recipes page 584

if \(wk1[jmax] \gt Fc\) then begin
    \(\text{lnperrctr} = \text{lnperrctr} + 1\)
    \(\text{lnpsigflg} = 0\)
end if
endif else \(\text{lnpinsigctr} = \text{lnpinsigctr} + 1\)
endif else begin
    Skip periodogram
    \(\text{lnskipctr} = \text{lnskipctr} + 1\)
end else

; Curve Fit
; fit a cosine curve with fixed value of normal freq
; of the highest peak when one exists
if \((\text{lnpsigflg} \eq 1)\) then begin
    \(\text{lnpfittcr} = \text{lnpfittcr} + 1\)
    \(\text{ni} = wk1[jmax]\)
    \(\text{pp} = \text{replicate}([\text{fixed}:0, \text{limited}:[0,0],\)
                    \text{limits}:[0.D,0.D]},4)\)
    \(\text{pp}[2].\text{fixed} = 1\)
    \(\text{p0} = [0.,1,\text{ni},0.1]\)
    \(\text{X} = \text{xdef}[\text{back}]\)
    \(\text{cn} = \text{y}[\text{back}]\)
    \(\text{sigyfit} = \text{sigy}[\text{back}]\)
    \(\text{expr} = '{\text{p}[0]} + \text{p}[1]\text{cos(2*!dpi*p[2]*X+p[3])}'\)
end if

prewhiten (subtract fitted curve from observations)

\(\text{p} = \text{mpfitexpr}('\text{expr}, \text{X}, \text{cn}, \text{sigyfit}, \text{p0}, \text{PARINFO}=\text{pp},\)
         \text{PERROR}=\text{perr}, /QUIET)\)
\(\text{cef1} = \text{cos(2*!dpi*p[2]*xdef+p[3])}\)
\(\text{cef2} = 2*!dpi*xdef*\text{sin(2*!dpi*p[2]*xdef+p[3])}\)
\(\text{cef3} = \text{sin(2*!dpi*p[2]*xdef+p[3])}\)
; apply fit to time series for this pixel
\(\text{y} = \text{y} - (\text{p}[0]+\text{p}[1]*\text{cef1})\)
\(\text{sigy} = \text{sqrt(\text{sigy}*\text{sigy}+\text{perr}[0]*\text{perr}[0]+(\text{cef1}*\text{perr}[1])^2.+\)}\)
\((\text{cef2}*\text{perr}[2])^2.+((\text{cef3}*\text{perr}[3])^2.)\)
end if
IF \((j \eq 2*i)\) and \((\text{outflag} \eq 1)\) then begin
; reset from postscript plotting
Device, /CLOSE
Set_plot, 'x'
LOADCT, 0, /SILENT
\(\text{red} = \text{xred}\)
\(\text{green} = \text{xgreen}\)
\(\text{blue} = \text{xblue}\)
end if
endif else begin
; skip bad side of array
endelse
; linear+periodic baseline subtracted maps
indata[i,j,0:nonstim-1] = transpose(y)
; linear+periodic baseline subtracted error maps
insigma[i,j,0:nonstim-1] = transpose(sigy)
; pixel mask has values 0 and 1 only
mask1[i,j,0:nonstim-1] = transpose(mmask)
endfor

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
; Main Iteration END: go through "good" pixels
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
sub    = replicate(0.0D, y1, y2)
sky    = sub
scount = replicate(0, y1, y2)
icle   = replicate(1, y1, y2)

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
; Output
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
; Output
; Run through all files. When stim is off, grab the results
; from above and rewrite the data values.
; Write out FITS with modified filenames.
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
nstim = 0 ; counter for nonstim frames
for i=0,nfiles-1 do begin
  cd, bcdpath
dat = readfits(filelist[i],head,/NOSCALE,/SILENT)
err  = readfits(filelist2[i],head2,/NOSCALE,/SILENT)
sunc = err
if (offstim[i] eq 1) then begin
  yfit = indata[*,*,nstim]
sigy = insigma[*,*,nstim]
tmp  = dat - yfit ; sky at nonstim timing[i]
; recover bmask file names from bunc file names
tmpstr = strsplit(filelist2[i],'bunc',/EXTRACT,/REGEX)
fmask = string(strjoin([tmpstr[0],'bmask',tmpstr[1]]))
tmp1  = readfits(fmask,head3,/NO_UNSIGNED,/SILENT)
; update data arrays with valid data
  on = where(finite(dat))
  on = where(finite(dat) and (mask1 eq 0))
dat[on] = yfit[on] ; sky-subbed good pix data at timing[i]
err[on] = sigy[on] ; sky-subbed good pix error at timing[i]
sky[on] = sky[on] + tmp[on] ; sum of sky up to timing[i]
scount[on] = scount[on] + incle[on]; valid data points up to i
nstim = nstim + 1 ; increment counter
; Sky uncertainty processing
For k = 0, y1-1 do begin
  For l = 0, y2-1 do begin
    IF (finite(err[k,l]) eq 1) AND $(finite(sigy[k,l]) eq 1) $ THEN BEGIN
      sunc[k,l] = sqrt(err[k,l]^2 + sigy[k,l]^2)
    ENDIF ELSE BEGIN
      sunc[k,l] = err[k,l]
  endelse
endfor

150
ENDELSE
Endfor
EndFor
endif
if (outflag eq 1) or (skyflag eq 1) then begin
; Create updated FITS files with new names
  tmp2     = strsplit(filelist[i],'/','LENGTH','/REGEX)
  ts       = size(tmp2)
  tmpstr   = strsplit(strmid(filelist[i],tmp2[ts[1]-1]),'
  bcd','/EXTRACT','/REGEX)
  newname  = string(strjoin([tmpstr[0],'lnp_bcd',tmpstr[1]])
  newname2 = string(strjoin([tmpstr[0],'lnp_bunc',tmpstr[1]])
  newname3 = string(strjoin([tmpstr[0],'lnp_sky',tmpstr[1]])
  newname4 = string(strjoin([tmpstr[0],'lnp_sunc',tmpstr[1]])
  cd, lnppath
endif
if (outflag eq 1) then begin
; Write out FITS files keeping old header
  writefits, newname,  dat, head
  writefits, newname2, err, head2  ; New uncertainty files
endif
IF (skyflag eq 1) then begin
  writefits, newname3, FLOAT(tmp), head ; bcd level sky data
  writefits, newname4, FLOAT(sunc), head2 ; sky uncertainty
ENDIF
endfor
;
  sky = sky/scount
;
  writefits, 'sky_slope.fits', slope
  writefits, 'sky_intercept.fits', intercept
  writefits, 'sky_average.fits', sky
;
  openw, lun, 'medsky.txt', /get_lun
  printf, lun, median(sky), FORMAT='("Median SKY = ", g13.6)'
  free_lun, lun
;
if (perflag eq 1) then begin  ; Write periodogram data to file
  iter = pixdim
  FILESTRING='Periodogram.txt'
  GET_LUN, Unit
  OPENW, Unit, FILESTRING
  fidx = 0
  WHILE (fidx LT iter) do begin
    If freqdata[fidx].freq gt 0 then begin
      printf, Unit, freqdata[fidx]
    endif
    fidx = fidx + 1
  ENDWHILE
  CLOSE, Unit
  FREE_LUN, Unit
endif
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
; Calculate sky median and standard deviation

; Calculate sky median and standard deviation
i = 0L & n=0L & m=0L
skymed = 0.0D
skysd  = 0.0D
skymed = median(sky, /even)
ssize  = N_ELEMENTS(sky)
sky1D  = fltarr(ssize)
for n = 0, y1-1 do begin
  for n = 0, y2-1 do begin
    sky1D[i] = sky[n,m]
    i = i + 1
  endfor
endfor
skysd  = stddev(sky1D, /DOUBLE, /NAN)

; Diagnostics

print, ' Source star:          ', source
print, ' Total number of BCDs: ', nfiles
print, ' Stim BCDs:            ', stimctr
print, ' Nonstim BCDs:         ', nonstim
print, ' Total nonstim pixels: ', totpix
print, ' Bmask pixels:         ', mcount
print, ' NAN pixels:           ', NANctr
print, ' Number of Periodogram calls:           ', lnpctr
print, ' Number with significant frequencies:   ', lnpsigctr
print, ' Number with insignificant frequencies: ', lnppinsigctr
print, ' Number of skipped calls:               ', lnpskipctr
print, ' Nyquist frequency for the dataset:     ', Fc_data
print, ' Number of Fourier fits completed:      ', lnpf
print, ' Number of Fourier fits skipped:        ', lnpskipctr
print, ' Number of times first pass skipped:    ', pass1ctr
print, ' Number of times second pass skipped:   ', pass2ctr
print, ' Number of invalid first pass thresholds: ', invalidctr
print, ' Rejected pixels:      ', pxreject
print, ' Kept pixels:          ', pxkeep
print, ' Limit:                ', arcsec_limit, ' arcseconds'
print, ' Median SKY = ', skymed
print, ' Standard deviation sky = ', skysd

end_time = systime(1, /seconds)
elapsed_time = end_time - begin_time
print, ' Elapsed time: ', elapsed_time, ' seconds'
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end