A Study of Transient Variations in Cosmic Ray Proton Intensities Using BESS-Polar I Data

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A Study of Transient Variations in Cosmic Ray Proton Intensities Using BESS-Polar I Data

A Dissertation

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the Faculty of Natural Sciences and Mathematics

University of Denver

In Partial Fulfillment

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Doctor of Philosophy

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Neeharika Thakur

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Abstract

The intensities of galactic cosmic rays are modulated upon entering the heliosphere. These variations, defined as solar modulations, are classified as long-term or transient modulations based on their durations.

Studies have correlated the transient variations with the characteristics of the solar wind and the interplanetary magnetic field. Therefore, studies of transients augment our understanding of physical processes in the interplanetary medium. Processes causing transient variations may also induce geomagnetic storms. Precise measurements of cosmic ray fluxes during a transient phenomenon will have immense use in validating models of space weather prediction.

BESS (Balloon-borne Experiment with a Superconducting Spectrometer), a US-Japanese collaborative program, directly measures light elements of cosmic rays in a large energy range (∼0.1 - several hundred GeV) thus bridging the gap between the low energy space-based and high energy ground-based experiments, has a large geometrical acceptance (0.3 m² sr), and is highly sensitive in the lowest energy regime of cosmic rays where the solar modulations occur. BESS measurements can provide study of transient variations of cosmic ray protons and helium, for same energy but different rigidities (momentum per unit charge) or the same rigidity but different energies, as separate probes. BESS is sensitive to diurnal variations, unlike space based experiments.

Proton fluxes from BESS-Polar I (flown from Williams Field, Antarctica, December 13-21, 2004), calculated for energies 0.1-100 GeV in time intervals as short as 4 hours, are analyzed for variations. Energy dependence of the observed variations is explored
using smaller energy intervals. Neutron monitor data support our observations. To our knowledge, this is the first direct measurement of variations at the few-1% level by a balloon or satellite experiment at time scales of a few hours.

Proton fluxes are presented in 4-hour averages, suitable for validation of solar wind and space weather prediction models. Suggested physical interpretations of the three observed features in the proton spectra, derived by comparison with the solar wind and IMF data from space-based experiments, include presence of a corotating interaction region or a magnetic cloud or a combination of both, a turbulent interaction region, and Compton-Getting anisotropy.
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Chapter 1

Introduction

The primary galactic cosmic rays (GCRs) consist of energetic charged particles and have been observed in a wide range of energies, from \( \sim 100 \text{ MeV} \) to beyond \( \sim 10^{12} \text{ GeV} \). The components of cosmic radiation include cosmic ray electrons (\( \sim 2\% \)) and completely ionized nuclei (\( \sim 98\% \)) starting from the hydrogen nucleus (proton) all the way up to the uranium region in the periodic table of elements. The cosmic nuclei are composed of 87% hydrogen nuclei, 12% helium nuclei, and 1% all other heavier nuclei \[85\]. The galactic cosmic rays have an abundance distribution similar to that in solar system material. Away from the Earth their arrival directions are isotropically distributed to 1 part in 1000. Prior to its detection near the Earth, each cosmic ray particle was accelerated at its source, traversed the interstellar medium, and entered the heliosphere\(^1\), which it traversed before reaching the Earth.

As the galactic cosmic rays enter the heliosphere, their intensities are modulated due to the effects of solar magnetic field and physical processes taking place in the heliosphere. Signatures of solar atmosphere and a magnetic field of solar origin are carried into the heliosphere by the solar wind\(^2\), and hence the physical conditions in

----

\(^1\)The region contained within the boundaries of the solar system.

\(^2\)The plasma ejected radially outward from the surface of the Sun. It permeates throughout the
the heliosphere are dominated by the Sun. Therefore, the variations in cosmic ray intensities are known as solar modulations. The solar modulations are classified as long-term or short-term based on their durations. Long-term modulations are related to the 11-yr and 22-yr solar activity cycles. Short-term modulations are observed near the Earth when the Earth passes through any short-term disturbances introduced in the heliospheric plasma due to any sudden, transient solar activity.

This chapter discusses presented study and the motivation behind it, elucidates why BESS (Balloon-borne Experiment with a Superconducting Spectrometer) observations provide a unique set of measurements for this work, and presents an outline of this dissertation.

The next section outlines the research presented in this dissertation.

### 1.1 Presented study

For the study in this dissertation, I define a transient variation as any variation in the cosmic ray intensities that can be observed by a BESS-Polar long duration balloon (LDB) flight of duration of $\sim 10 - 20$ days.

This dissertation presents measurement of short-term variations in cosmic ray proton flux intensities using the BESS-Polar I data.

Cosmic ray proton fluxes have been calculated from BESS-Polar I measurements between energies 0.1 - 100.0 GeV. Time variation of these fluxes is explored for daily and 4-hour time intervals in this energy range. To explore energy dependence of the observed variations, the 4-hour fluxes have been studied for smaller energy intervals within the above energy range. BESS-Polar I proton fluxes are presented in time intervals of 4 hours such that they can be used for validation process of various solar wind and space weather prediction models. Presented few-1% level variations on few hour time scales heliosphere.
emphasize the sensitivity of BESS measurements. To our knowledge such small scale variations at these time scales have never been directly measured before by a balloon or satellite experiment.

A detailed comparison of BESS-Polar I data with those from comparative experiments corroborates that observed variations are real. Then BESS-Polar I observations are compared with parameters characterizing the heliosphere, especially the properties of solar wind and interplanetary magnetic field. These comparisons establish that there are apparent correlations between BESS-Polar I measurements and physical conditions of local heliosphere. Based on comparisons with solar activity and solar wind plasma in the near-Earth regions, some possible physical interpretations are suggested for the observed transient variations.

It must be noted that the study presented in this dissertation is based on measurements made by BESS-Polar I. I participated in the instrumentation and launch of BESS-Polar II.

The next section explains the motivation for the presented research.

1.2 Scientific motivation

Study of cosmic ray variations contributes to our understanding of local conditions in the heliosphere as well as in the modeling of particle fluxes and plasma conditions in the near Earth environment, a discipline known as space weather. Space weather is of interest because the local plasma affects the Earth’s magnetosphere and its geomagnetic and geoelectric currents.

\[\text{3}\text{The magnetosphere is formed when the solar wind interacts with and is deflected by the intrinsic magnetic field of the Earth. The shape of magnetosphere is determined by the solar wind, geomagnetic field, and the interplanetary magnetic field.}\]
1.2.1 Physical processes in the local heliospheric regions

Cosmic ray variations play a significant role in reflecting physical processes in the interplanetary medium [84]. Studies have shown that short term variations are correlated with the characteristics of the solar wind and the interplanetary magnetic field\(^4\). Several theories have been developed to explain short-term variations but are often inconsistent with each other and do not make more than general predictions. A study of the literature shows that by no means is our knowledge of the physics of the transient variations of the cosmic radiation complete. Therefore, a detailed study of any transient phenomenon, observed through the variations in cosmic ray intensities, augments our comprehension of the plasma processes that may have caused the modulations. A careful comparison of the unmodulated and modulated fluxes enables a better insight into the physical processes existing in the heliosphere.

1.2.2 Validation of models for space weather predictions

While the thick neutral atmosphere and geomagnetic field strongly shield the Earth’s surface from the galactic cosmic rays at the equatorial regions, the cosmic rays can directly enter the atmosphere in the polar regions and can affect the polar ground-based instruments as well as polar-orbiting instruments situated at lower altitudes. A heavy cosmic ray ion particle or an interacting proton can deposit enough charge at a sensitive portion of electronic circuit resulting in a change of state in the circuit, thus rendering the instrument inoperable. Such an event is called a single event upset (SEU). In addition, highly ionizing heavy nuclei, like Fe, can cause severe tissue damage in humans. Thus the galactic cosmic rays can adversely affect the humans in long duration space flights outside the Earth’s magnetic field and in the polar transiting aeroplanes [21]. Some solar activities can also initiate geomagnetic storms.

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\(^4\)The magnetic field in the interplanetary regions. This is of solar origin and is carried outward from the Sun by the solar wind.
Therefore, an accurate prediction of space weather becomes important. Theoretical models are used for such predictions. Measured precise spectra of cosmic rays during any short-term variations can be applied to validate and improve such theoretical models. One of the main concerns of the modeling community is the lack of real data along with accurate error bars. Precise proton fluxes from BESS can be used for this purpose.

The next section explains the importance of BESS measurements in this regard.

1.3 Benefits of BESS-Polar data

BESS is a US-Japanese collaborative program which has had 11 successful scientific flights since 1993. The institutions comprising the BESS collaboration are shown in Figure 1.1.

The main scientific goals of the BESS program include searches for cosmological antimatter and precise measurements of proton, deuterium, $^3$He, and $^4$He in the cosmic radiation. The goal addressed in this dissertation is a study of the short-term variations in the cosmic ray flux. The study of short-term transients is a new field of study for BESS and has been made possible by the long duration circumpolar BESS flights, known as BESS-Polar flights.

In order to achieve its goals, BESS carries out studies of low energy antiprotons, specifically collection of enough antiprotons to characterize their absolute intensity, extensive searches for antihelium and antimatter nuclei in the cosmic radiation, direct searches for cosmic antimatter to investigate the matter/antimatter asymmetry in the universe, precise measurements of the light elements and composition in the cosmic radiation. Mitchell et al. have presented a review of the BESS program [51].

Two BESS-Polar flights successfully commenced from Williams Field near McMurdo Station, Antarctica. BESS-Polar I took place from December 13 - 21, 2004 at an average float altitude of $\sim 37$ km with an average residual atmosphere (overburden) of 4.3 g/cm$^2$. 
and recorded $9 \times 10^8$ cosmic ray events in 8.5 days. BESS-Polar II flight occurred from December 23, 2007 to January 21, 2008 at an average float altitude of $\sim 37$ km with an average overburden of $5 \text{ g/cm}^2$, and recorded $4.7 \times 10^9$ cosmic ray events in 24.5 days.

BESS makes measurements in a much larger energy range compared with small satellite instruments, which operate at lower energies, that have been used to study these phenomena in the past. The neutron monitors\(^5\) operate at higher energies and don’t measure the particles directly. Thus BESS bridges an important energy gap between the space-based and ground-based measurements. There is an overlap of energies between BESS and neutron monitors (typical neutron monitor energy $\sim 2 - 10 \text{ GeV}$ where it is most sensitive), making the neutron monitors good comparative experiments for our measurements. Interaction of charged particles in a magnetic field is characterized by the particles’ gyroradii in the magnetic field. For a given magnetic field, higher energy particles deflect less and lower energy particles deflect more from their original paths.

\(^5\)Ground-based detectors that count the rates of neutrons created by the interaction of incident cosmic rays with the atmosphere.
This phenomenon is described by a physical quantity, rigidity\textsuperscript{6} of the particle. BESS can use proton and helium, same energy but different rigidities or same rigidity but different energies, as separate probes whereas the neutron monitors see some kind of flux averaged over a band of effective sensitivity. It must be noted that the solar modulation is low at higher energies and there is no significant modulation for energies $> 10^{10}$ eV. To our advantage, BESS has high sensitivity to the low energy particles which undergo a higher degree of modulation. The BESS energy range for protons is $\sim 100$ MeV to a few hundred GeV. BESS-Polar recorded all incident events that triggered the system and measured their charge, mass, and energy.

BESS has a much greater geometrical acceptance compared with other similar experiments. For example, the geometrical acceptance of BESS is 3000.0 cm\textsuperscript{2} sr whereas for a similar satellite based experiment, PAMELA \textsuperscript{[99]}, it is 21 cm\textsuperscript{2} sr. Hence, BESS has greater collecting power at low energies by $\sim$ an order of magnitude. PAMELA observations are of time scale $\sim$ 3 years, making it a good experiment for long-term measurements. BESS-Polar observations last only for 10 - 20 days and BESS is optimal for high precision short-term studies. BESS-Polar flights provide a long enough time frame to observe cosmic rays during a transient phenomenon. In addition, both, BESS-Polar I and II observed transient variations, thus a combined analysis from both the flights can provide a better insight into the physics of local regions during variations.

A survey of literature does not reveal many studies of short term transient effects on the cosmic ray flux by balloon data; it may be because unlike BESS other similar balloon experiments did not have high geometrical acceptances or the experiments with similar or better geometrical acceptance did not explore cosmic radiation for short-term variations.

A brief list of topics and analysis included in this dissertation is provided next.

\textsuperscript{6}Rigidity is defined as momentum per unit charge.
1.4 Layout of this dissertation

Due to my participation in the instrumentation, flight of BESS-Polar II, analysis of the data, and an attempt at physical interpretation of the observed variations, this dissertation describes the experiment, data analysis, and some theory. The remaining chapters of this dissertation are arranged as follows:

Chapter two contains a brief introduction to cosmic rays, their energy spectrum, and their propagation in the galaxy and heliosphere. A short description of cosmic ray modulations and their types as well as importance of their studies is given in chapter three. Chapter four has an overview of the BESS program, its measurement technique, and instruments aboard BESS-Polar detector. Details of my participation in the instrumentation of time-of-flight detector and balloon campaign of the BESS-Polar II are provided in chapter five.

The analysis of BESS-Polar I proton data is described in chapter six. This chapter explains calculation of proton flux, observed daily variations in their fluxes, observed variations and features in the cosmic ray proton flux for 4-hour time windows, and presents the time progression of these fluxes for 4-hour time intervals.

Chapter seven compares the time progression of BESS proton fluxes with neutron monitor data and characteristics of solar wind plasma and interplanetary magnetic field, and suggests possible causes for features observed in our proton flux. Conclusions are summarized and suggested future studies to improve upon the presented analysis are provided in chapter eight.
Chapter 2

Cosmic Rays - A Brief Introduction

This chapter provides a very brief introduction to the galactic cosmic ray spectrum, propagation of cosmic rays in the Galaxy, and the basic features of the heliosphere and Earth’s magnetosphere.

2.1 Cosmic rays

The study of cosmic rays originated approximately in 1900 but their definitive discovery was made by Victor Hess in 1912 during his famous balloon flight that reached an altitude of 5 km [67]. The primary cosmic ray particles interact with the particles in the interstellar medium and produce secondary particles as they traverse space. For this dissertation, primary cosmic rays enter the top of Earth’s atmosphere and then interact in the atmosphere to produce secondaries, which in turn can interact further to produce more secondary particles.

Basic features of the cosmic ray spectrum are discussed next.
2.1.1 Energy spectrum of cosmic rays

Figure 2.1 shows the classic spectrum of cosmic rays, as observed near the Earth. At energies above 1 GeV, the spectrum follows a power law energy distribution and below 1 GeV there is an attenuation relative to this power law distribution primarily due to solar modulation. Such attenuation is enhanced during solar maxima when the interplanetary magnetic fields are more disturbed. For energies greater than 1 GeV the cosmic ray flux decreases rapidly with increase in particle energies. For energies 10^{10}-10^{15} eV, the differential spectrum, $dF_i(E)$ of a species $i$, of cosmic ray particles in the energy interval from $E$ to $E+dE$ is expressed by

$$
\frac{dF_i(E)}{dE} \propto E^{-\gamma_i}
$$

(2.1.1)
where, $2.5 \leq \gamma_i \leq 2.7$ and $E$ is expressed as kinetic energy per nucleon [89]. For protons $\gamma_p \approx 2.7$ [67]. The slope of the spectrum undergoes a subtle change around $E \sim 3 \times 10^{15}$ eV where the spectrum becomes steeper and the spectral index changes from 2.7 to 3.0. The slope of the spectrum changes again around $E \approx 10^{17}$ eV and the spectral index becomes $\sim 3.3$. The region between the two slope changes is known as the “knee” of the galactic cosmic ray spectrum. Some people refer to the second point of change as a “second knee”. Beyond $E \approx 10^{18}$ eV the cosmic ray spectrum flattens and the spectral index becomes 2.6. This is known as the “ankle” of the cosmic ray spectrum [122].

At the lowest energy end, the 100 MeV particles are non-thermal and are important sources of heating and ionization of the interstellar medium (ISM) and experience higher attenuation.

We have the most information for the part of spectrum that is below the “knee” because the flux is large. Cosmic rays with energies up to $10^{15}$ eV are believed to have been created in the Galaxy. Supernova are the only sources with sufficient energies to accelerate and maintain the flux in the Galaxy. Acceleration of cosmic rays by a supernova can occur during the explosion process, in the pulsar that is left behind, in the envelope, or at the shock waves formed by the fronts in middle aged supernova explosion envelopes. In addition, the supernova envelopes are sources of synchrotron radiation and hence contain relativistic electrons. Two processes, known as Fermi’s first and second order acceleration explain acceleration of cosmic rays by supernova explosions [86].

In the first order Fermi acceleration process particle acceleration takes place by collisionless plasma shocks. When a charged particle is reflected from a shock, it can gain energy proportional to $\beta$ where $\beta = v/c$. This process produces a power law spectrum with a slope determined by the strength of the shock. The second order Fermi acceleration relates to acceleration of charged particles by a magnetic field. When a charged particle collides with a moving magnetic field, it can either gain energy or lose energy. If the
magnetic scattering center is moving towards the particle, the particle will reflect back with increased energy. If the magnetic scattering center (or magnetic “mirror”) is moving away from the particle, the particle will lose some of its energy. Since encounters with shocks moving towards the particle are more likely, multiple interactions with the moving magnetic field will accelerate the cosmic ray particle over time. The energy gain is $\propto \beta^2$ of the particle. This mechanism also produces a power law that agrees with the observed spectrum of the galactic cosmic rays. The favored mechanism is shocks in the envelope.

The magnetic fields on the Sun and other stars also accelerate particles. It has been seen that our Sun produces cosmic rays and it is a relatively quiet star. Therefore, stars like Novae, magnetic stars of type A, hot stars of type O, and binary stars can also probably accelerate cosmic rays. However, these stellar sources do not have enough energy to fill the Galaxy with cosmic rays.

The acceleration mechanisms for particles with energies between $10^{15} - 10^{18}$ eV are not well understood. Theoretical considerations suggest that supernova remnants (SNR) cannot produce particles with energies beyond $10^{15}$ eV. However, observational results indicate that these cosmic rays are generated within the Galaxy.

Regardless of the actual individual sources accelerating the galactic cosmic ray particles, the majority of sources are concentrated towards the galactic disk.

The Ultra-High Energy Cosmic Rays (UHECR) have energies beyond $10^{18}$ eV. The galactic cosmic ray sources can probably only accelerate particles up to $\sim 10^{18}$ eV. No known galactic source can produce particles of such high energies. Due to their high energies the deflection of these particles in the weak magnetic field of our galaxy is small and observations show that these particles do not arrive from the disk or center of our galaxy so the UHECRs must have an extragalactic source. At these energies the flux is so small that it becomes difficult to detect the particles. Fluxes of UHECRs are limited by the Greisen-Zatespin-Kuzmin (GZK) cutoff, which provides the theoretical upper
limit for energy of a cosmic ray particle based on their interaction with the photons of cosmic microwave background (CMB). This indicates that there should be a pile-up of cosmic rays around the energy $\sim 10^{19}$ eV beyond which the cosmic ray spectrum should steepen. However, a few cosmic ray particles beyond this energy have been observed. The Pierre Auger Observatory studies these particles through large air shower detectors [94].

The galactic cosmic rays are scattered into an isotropic distribution by interactions with galactic magnetic fields, making it difficult to infer anything about their origin using directional measurements. However, the UHECRs undergo only minor deflection in galactic magnetic fields, giving some idea of their point of origin but no such sources have been detected yet [122].

2.1.2 Elemental and isotopic abundances in cosmic rays

Elemental abundances

Abundances of elements in cosmic rays provide information about the abundances at their sources of acceleration and the physical processes involved in their synthesis. Figure 2.2 shows a comparison between the chemical abundances in the cosmic rays and solar system materials. While there are general similarities, the differences are a source of information and study. Both show: (1) presence of abundance peaks at carbon, nitrogen, oxygen, and iron group; (2) presence of “odd-even effect” in relative stabilities of nuclei according to atomic number. Differences between cosmic ray and solar abundances include: (1) cosmic rays have higher abundance of light elements; lithium, beryllium, boron compared with their solar abundances; (2) cosmic rays have excess abundance for elements between calcium and iron; (3) cosmic rays have an under abundance of hydrogen and helium relative to heavier elements. The higher abundance in cosmic rays of the elements Li, Be, B and elements between calcium and iron can be
explained by spallation. During their passage through interstellar space, the cosmic rays interact with the particles therein and fragment into nuclei lower in atomic number, thus increasing the abundance of lighter elements. Abundances of heavy elements relative to iron are similar in both cosmic ray and solar chemical abundances [85].

These similarities suggest that cosmic rays must have been accelerated at sources that have chemical composition similar to the solar system’s.

**Isotopic abundances of cosmic rays**

Isotopic abundances are of importance. A special group of isotopes contains $^1$H, $^2$H, $^3$He, and $^4$He out of which only $^1$H and $^4$He have high abundance as in solar system and universal abundances. Spallation within these species is one of the explanations for the abundances of $^2$H and $^3$He. Some of the species created in spallation of cosmic rays are radioactive. Therefore, if production rates of these isotopes are known, the time taken by these particles to reach the Earth after their acceleration at sources can be calculated. The most common isotopes of heavier elements have similar abundances in cosmic rays and solar system but in several cases abundances of a few rarer elements are much higher in cosmic rays. These aspects help determine the origin of cosmic rays.

![Figure 2.2: Cosmic ray elemental composition (relative to Si) (figure from [11])](image-url)
2.2 Propagation of cosmic rays

The propagation of cosmic rays is better understood in the regions near the Earth and less understood as we move away from the Earth into the heliosphere and outside the solar system. Heliosphere is the region that surrounds the Sun and extends beyond the orbit of Pluto and into the interstellar medium. This section begins with a brief description of propagation of cosmic rays in the Galaxy. Then an introduction to characteristics of the heliosphere and Earth’s magnetosphere is provided because processes in these regions influence the spectra of galactic cosmic rays; this is especially relevant to the topic of this dissertation. After its production a cosmic ray particle traverses the Galaxy, the heliosphere, and the magnetosphere before it is detected near the Earth. This is the order in which the propagation of cosmic rays is discussed here.

2.2.1 Propagation in the Galaxy

Propagation of the galactic cosmic rays takes place mainly via diffusion. Some convection of particles in the plasma is also indicated. There can be energy loss mechanisms that reduce density of particles in a certain energy/momentum range. The propagation can be described by an equation of propagation which takes into account all possible mechanisms that may increase or decrease the cosmic ray density at a location about a momentum. The cosmic ray propagation equation for a particular particle species is described by a diffusion-convection equation that takes account of energy losses and gains as well as fragmentations. This equation can be written in the general form [10]:

\[
\frac{\partial \Psi(\vec{r}, p, t)}{\partial t} = q(\vec{r}, p, t) + \nabla \cdot (D_{xx} \nabla \Psi - \vec{V} \Psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \Psi \\
- \frac{\partial}{\partial p} \left[ p \Psi - \frac{p}{3} (\nabla \cdot \vec{V}) \Psi \right] - \frac{1}{\tau_f} \Psi - \frac{1}{\tau_\gamma} \Psi
\]
where, $\Psi(\vec{r}, p, t)$ is the cosmic ray density per unit of total particle momentum $p$ at position $\vec{r}$, $\Psi(p) dp = 4\pi^2 f(\vec{p}) dp$ in terms of phase space density $f(\vec{p}) dp$, $q(\vec{r}, p, t)$ is the source term for the cosmic ray particle (his includes primary particles as well as contributions through spallation and decay), $D_{xx}$ is the spatial diffusion coefficient, $\vec{V}$ is the convection velocity, $D_{pp}$ represents the diffusive reacceleration which is described as diffusion in momentum space, $\dot{p} = \frac{dp}{dt}$ is the rate of momentum gain or loss, $\tau_f$ is the timescale of loss of particles by fragmentation, and $\tau_\gamma$ is the timescale for radioactive decay. Here, $D_{pp} D_x \propto p^2$.

**Main modes of transport of galactic cosmic rays**

Diffusion, convection, and reacceleration processes affect the distribution of cosmic rays in the Galaxy. These processes are briefly explained in this section.

**Diffusion**

Diffusion is the main mode of transport for the cosmic rays of energies up to at least $10^{15}$ eV. The diffusion of cosmic rays is caused by the scattering of the particles with the random magnetohydrodynamic (MHD) waves and magnetic discontinuities. These MHD waves are generated as a result of perturbations in the magnetized plasmas. The cosmic rays interact with the galactic magnetic field, such interactions alter their trajectories are altered. As a result, cosmic rays have highly isotropic distributions and long (20 Myr) residence time in the Galaxy.

**Convection**

In the cases where galactic wind and hence a bulk motion of the plasma are present, convection can carry particles out of the system and represent a loss mechanism for loss of particles from the system. The plasmas in space have high electrical conductivity, i.e., the particles have very long mean free paths and in the limit of infinite conductivity
the magnetic field behaves as if it were “frozen-in” the plasma. Within galaxies there can be a large scale motion of the interstellar gas that carries a “frozen-in” magnetic field. The cosmic rays also participate in this motion and can be transported as a whole. Convection can also produce adiabatic energy losses as the wind speed increases and the plasma expands away from the disk. This becomes important because galactic winds exist in many galaxies and can be driven by the cosmic rays. Thus cosmic rays also play a dynamical role in galactic halos.

Reacceleration

The relativistic particles can achieve some additional acceleration in the interstellar medium through the second order Fermi process. The process of distributed acceleration in the interstellar medium is classified as reacceleration in order to distinguish it from the acceleration that takes place in the compact source. Scattering of cosmic rays by MHD waves, which produces spatial diffusion, also results in stochastic acceleration. Some reacceleration is almost unavoidable and there are some indications that this is important for particles of low energies.

At higher energies (~ 1-100 GeV/nucleon) the acceleration of the cosmic rays cannot solely be caused by the distributed acceleration in the entire galactic volume, because, if it were true, the higher energy particles would have to spend longer time in the Galaxy to attain such energies and this would lead to relative higher abundances of the secondaries as the energy increases. This is not supported by observations. The data on the secondary nuclei prove that there is very little strong reacceleration at the higher energies.

In the process of reacceleration, the particle gains energy and there is a corresponding energy loss of the interstellar MHD turbulence.
2.2.2 Propagation in heliosphere

The Sun’s atmosphere plays an important part in the physical conditions of the heliosphere. The solar atmosphere can be divided into photosphere, chromosphere, and corona. The photosphere is a layer with thickness of about 500 km and temperature around $\sim 5800$ K. Above the photosphere, the chromosphere extends up to the height of 2500 km with temperatures ranging from $\sim 4500$ - $10000$ K. The chromosphere merges into the corona which extends out to millions of miles and has temperatures up to $10^6$ K at its base. The temperature subsequently decreases in the corona as it expands into the interplanetary space. This expanding corona is the solar wind plasma with a magnetic field and involves charged particles, mainly electrons and protons [101]. The solar wind has a typical speed of $\sim 300$ - $800$ km/s.

Heliosphere

Before their detection near the Earth, cosmic rays must propagate through the heliosphere. The heliosphere contains materials and magnetic field of solar origin that are carried away from the sun by the solar wind. This magnetic field, known as the heliographic magnetic field, pervades the heliosphere. This magnetic field is “frozen-in” the plasma, and changes due to turbulent motion of particles therein. The structure of the “frozen-in” magnetic field can be described by the Parker Spiral [100][101]. A diagram of development of “frozen-in” field spiral locus is shown in figure 2.3 [82]. The heliographic magnetic field has been measured by various experiments for distance of $\sim 0.3$ AU to beyond 65 AU and for latitudes from $\approx 80^\circ$ S to $\approx 80^\circ$ N. The part of the heliographic magnetic field that is close to the ecliptic plane, within the interplanetary regions, is called the interplanetary magnetic field (IMF). A typical magnitude of the IMF near the Earth is a few nT (e.g., 5 nT).
As the solar wind reaches the outer limits of the solar system, it encounters the interstellar medium. Due to the dynamics between these two plasmas a boundary is formed such that inside that boundary the solar wind and heliographic magnetic field dominate the environment and the region outside this boundary is controlled by the interstellar medium. This boundary is called the heliopause and encloses the heliosphere (figure 2.4). Voyager [70] has estimated the heliopause to be between \( \sim 86 - 151 \) AU from the Sun.

During sudden solar magnetic storms such as solar flares and coronal mass ejections, the Sun expels a larger number of energetic particles, known as the solar energetic particles (SEP), into the solar wind. Maximum energies for the SEPs are typically \( \sim \)
100 MeV but occasionally the Sun accelerates particles up to 10 GeV. The highest energy SEPs (with energies > 500 MeV) are observed on the ground as enhanced intensities of galactic cosmic rays, known as ground level enhancement (GLE)\(^1\). No such strong solar storms occurred during BESS-Polar I.

As the galactic cosmic rays enter the heliosphere and propagate upstream against the out flowing plasma, their motions are affected by the heliographic and interplanetary magnetic fields. In addition, effects of any short-term activity of the Sun are transported in the interplanetary region by the solar wind. As a result, the galactic cosmic rays are modulated. Hence, it is important to observe the solar activity through the solar wind parameters in conjunction with studies of short term variation of cosmic rays. This will help explain the possible causes for variations in the local heliospheric regions.

\(^1\)A GLE event is characterized by sudden, sharp increase (followed by an approximately exponential decay back to the pre-increase flux) in cosmic ray intensities due to solar activity. These events are observed by ground-based detectors such as neutron monitors and muon detectors.
Heliospheric current sheet

Measurements near Earth’s orbit show that the IMF points away from the Sun (positive polarity) for about half the solar rotation and points towards the Sun (negative polarity) for the other half of the rotation. Each interval of uniform polarity is called a sector and is a region on the ecliptic plane. The polarity pattern during a rotation is referred to as “sector pattern”. The Sun’s rotation axis is tilted by 7.5° with respect to the ecliptic plane, which rotates with the Sun. The surface that separates the positive and negative sectors, i.e., the outward and inward magnetic field directions of the solar dipole, is called the heliospheric current sheet (HCS)[25]. Structure of the HCS can vary with phase of the solar cycle with higher solar activity inducing more structures in the HCS and lower solar activity resulting in a flatter HCS. Hence, during a solar minimum the intensity flux of the cosmic rays is higher, whereas during a solar maximum the “frozen-in” field of the solar wind erects a more efficient barrier to the galactic cosmic ray transport, causing a decrease in the flux.

2.2.3 Propagation in Earth’s magnetosphere

Finally, the cosmic rays must penetrate Earth’s magnetic field. To the first order approximation, the geomagnetic field can be considered a dipole magnetic field with the field lines extending from the geomagnetic north pole to the geomagnetic south pole with the most important source of this magnetic field being the currents generated by Earth’s liquid core [82]. This magnet is immersed in the extended and expanding coronal atmosphere and its field interacts with the solar wind. Changing conditions in the interaction induce large scale currents that can affect Earth’s field. As a result a magnetosphere is formed (figure 2.5) whose size depends on the pressure balance between the solar wind and Earth’s magnetic field. The magnetosphere lies within the magnetopause, which is the boundary separating the regions dominated by the geomagnetic
field and the solar magnetic field. The shape of the magnetosphere is determined by the interaction between Earth’s magnetic field, solar wind plasma and the interplanetary magnetic field. The physical conditions within the magnetopause are controlled by the Earth and the outside is the interplanetary medium.

Due to the pressure of solar wind, the magnetosphere is compressed in the direction facing the Sun and elongated in the direction away from the Sun. The interaction of the magnetized solar wind with Earth’s magnetic field transfers part of momentum from solar wind to Earth’s magnetic field and stretches it in the direction of solar wind thus forming a magnetic tail. Sun’s ultraviolet rays ionize some of the neutral particles in Earth’s atmosphere. At higher altitudes collisions are less frequent and recombination of these ionized particles is slow, so a high altitude permanent ionosphere is formed, which extends from $\sim 60$ km to high up in the magnetosphere. At night there is no ionization, and hence recombination dominates. The boundary at the equator, known as plasmapause, is located around 3 - 4$R_E$ from the surface of the Earth. The plasmasphere is the region surrounded by the plasmapause and includes the ionosphere. The bow shock for the Earth is the boundary at which the speed of solar wind drops as it approaches Earth’s magnetosphere. At ionospheric heights the plasma sheet of the
Figure 2.6: The Van Allen radiation belts (figure from [1])

Earth is located between geomagnetic latitudes 60° - 70°. The particles in the plasma sheet are populated from the ionosphere and solar wind particles. A typical proton energy in the sheet is \( \sim 10 \) keV and a typical electron energy is \( \sim 1 \) keV [101].

**Van Allen radiation belts**

The radiation belts (figure 2.6) were discovered by James Van Allen and his colleagues in 1958. Earth’s atmosphere has two radiation belts, inner and outer, where charged particles are trapped.

**The inner radiation belt** is located above Earth’s ionosphere to about \( 2R_E \) and is populated mostly by secondary cosmic rays produced by interactions of galactic cosmic rays with Earth’s atmosphere. Most of these secondary particles are absorbed by Earth’s atmosphere but some escape towards space and get temporarily trapped in Earth’s magnetic field. These particles move along the magnetic field lines and eventually enter Earth’s atmosphere and do not survive long. However, the secondary cosmic radiation includes neutrons which are not affected by the geomagnetic field and hence move further away from the Earth. Free neutrons decay into protons, electrons and antineutrinos.
The average decay time for a neutron is about 10 minutes but some neutrons decay much faster while they are still in Earth’s magnetic field so the resultant protons get trapped by the magnetic field into orbits that do not return down to Earth’s atmosphere and hence the particles in the radiation belt survive for a long time; from a few hours to 10 years. Another source of particles in this belt is the solar MeV particles that are produced during a solar flare or coronal mass ejections. After their capture in the geomagnetic field, such particles can get accelerated and transported to the inner radiation belt.

The outer radiation belt has boundaries at the magnetopause, \( \sim 10R_E \), in the Sunward direction and \( \sim 1-2R_E \), closer to the Earth, in the direction away from the Sun. The particles in this belt, primarily electrons, have energies ranging from a few eV to hundreds of keV. The higher energy particles in this belt mostly come from the solar wind, while the ionosphere supplies most of the lower energy particles. A lot of the outer radiation belt particles come from the magnetotail plasma which can get pushed towards near the Earth during magnetic storms. At the end of such storms, the turbulent electric fields die away leaving the charged particles trapped in the outer radiation belts. The outer belt is not as stable as the inner belt because the particles can get lost in the interactions with the rarefied gas of the outer atmosphere. This belt is quite dynamic and changes in a few hours in response to any perturbations from outer magnetosphere.

**Cutoff rigidity**

The geomagnetic field shields the Earth from incoming cosmic ray particles. At a given location in the magnetosphere only particles with rigidities greater than a minimum rigidity can enter and particles below that rigidity are deflected back to space. This rigidity is known as the geomagnetic cutoff rigidity of the location. Some detailed explanations are given by Smart and Shea [115].
2.3 Summary

Cosmic rays carry important astrophysical information that supplements the information obtained from the electromagnetic radiation. Cosmic rays can be sampled directly from outside the solar system and not just observed via the electromagnetic radiation and therefore, understanding the sources that are responsible for producing and accelerating these particles to such highly relativistic energies will expand our knowledge of the structure and composition of our galaxy. Because of their reacceleration in the interstellar medium, a study of cosmic ray particles will also provide information on such processes as the interactions of cosmic rays with gas, dust and magnetic field in the Galaxy.

Study of relative elemental and isotopic abundance can provide knowledge of the source plasma as it was before the acceleration of the particle, including the nature, location, and composition of sources as well as about the physics of particle acceleration from study of particle species. The comparison of different species tells us more about the sources and about the physics of acceleration and transport than can be deduced from one source alone (e.g., comparison of solar cosmic rays and galactic cosmic rays). A careful study of UHECRs should allow identification of their arrival directions and hence of their sources. What makes the cosmic rays almost unique in astrophysics and their study especially significant and complementary to other disciplines is the fact that only they can provide a detailed elemental and isotopic sample of the current interstellar medium [10]. In addition, the cosmic rays can also provide energetic particles for use in high energy nuclear physics experiments. They provide basis for the experiments in particle physics, search for dark matter, search for cosmological antimatter, search for new particles, studies of nucleosynthesis, and probe for the origin of galactic and extragalactic diffuse gamma ray emission.

A brief description of the cosmic ray modulations is presented in the next chapter.
Chapter 3

Short-term Variations in Intensities of Cosmic Rays

This chapter provides an introduction to the modulation of cosmic ray intensities.

3.1 Solar modulation

Observations near the Earth show that galactic cosmic ray flux intensities vary in time. The first such observations were made by S. A. Forbush in 1938 during which seventeen months of continuous records from ion chambers located around the Earth showed that the variations in intensities were correlated world-wide [84]. There was a large change in intensities from 0-30° N latitude but little difference from 30-47° N. These time variations in intensities were independent of atmospheric phenomena and were originally assumed to be caused by the geomagnetic disturbances such as perturbations of the geomagnetic field during geomagnetic storms.

However, later observations from 1950s showed there was also a decrease in cosmic ray intensities at the geomagnetic pole which could not have been produced due to effects of ring current or geomagnetic field perturbations [109] [110], [112] [113]. Stud-
ies from neutron monitors showed that magnitudes of variations were much larger for
the lower energy particles and indicated that meteorological effects did not cause such
variations. In addition, a few sharp and non-recurring intensity decreases greater than
6% were observed which could not have been caused by geomagnetic field variations.
These analyses led to the conclusion that causes of the observed cosmic ray intensity
modulations were not terrestrial but that the modulating mechanism was probably re-
lated to the effects of solar activity. These modulations must depend on the heliospheric
conditions, especially in the region between Earth and the Sun. However, cosmic rays
observed near the Earth arrive from all directions and an observer near the Earth is
magnetically connected to conditions in the outer heliosphere therefore, a physical pro-
cess in the outer solar sphere may also contribute to observed cosmic ray modulations
[111], [104]. All these processes are governed by the Sun, and hence such variations in
cosmic ray intensities are known as the solar modulations of the cosmic rays.

Hence solar modulation is defined as the modulation of the intensity of galactic
cosmic rays upon their passage through the heliosphere. The temporal change in the
intensity of a specific component of the galactic cosmic radiation is defined as the mod-
ulation of that component.

The next section defines various types of solar modulations.

3.2 Types of solar modulations

As mentioned in chapter 1, based on their time-scales, the solar modulations are classi-
fied as long-term or short-term modulations.

3.2.1 Long-term modulations

These modulations include the 11-year or 22-year variations. These are caused by the
reversal of polarity of the solar magnetic field, which occurs ~ every 11 years, thus
inducing the 11-year modulation of the cosmic rays. The full cycle takes 22 years. The charge-sign dependence of the long-term modulations can be investigated by studying the particle/antiparticle ratios. Such studies show the long-term modulation to be polarity and charge sign dependent.

BESS provides a sensitive test of the various models of long term solar modulation by simultaneously measuring the cosmic ray fluxes of protons and antiprotons during its several flights since 1993. These measurements took place under a range of solar activity conditions (solar minimum, solar maximum, and reversal of polarity) [49]. The little variation in the ratio of $\bar{p}/p$ was consistent with the spherically symmetric models and the charge-sign dependent models of solar modulation [76],[72]. BESS observed a large increase in this ratio immediately after the reversal of magnetic field; such an increase is explained by the current drift models but not by the Force-field model. The $\bar{p}$ suffers less modulation than p because its local interstellar spectrum has a relative deficit of particles below 1 GeV due to kinematics of $\bar{p}$ production. Figure 3.1 shows comparison of BESS measurements with some theoretical models.

3.2.2 Short-term modulations

The short-term variations that BESS can observe include the 27-day variation, the diurnal variation, the transient variations that are not recurrent at specific time intervals, e.g., the Forbush decreases, ground level enhancements and other transients. This section provides brief description of various types of short-term cosmic ray variations.

Well-defined short-term variations

27-day variations The differential rotation of the Sun is apparently responsible for variations with periodicity of 27 days. There are also variations with periodicity of 13 or 14 days owing to the quasi-period of this differential rotation.
(a) \( \bar{p}/p \) ratio measured by BESS. Dash: drift model for \( A>0 \) tilt angle 65 deg. Dash-dot: \( A<0 \), 65 deg. Upper solid: \( A<0 \), 25 deg. Lower solid: \( A>0 \) 15 deg.

(b) variation of antiproton/proton ratio compared with drift models of Moskalenko et al. and Bieber et al.

Figure 3.1: Contribution of BESS in studies of long term modulations (figures from [49]).

**Diurnal variations:** The diurnal variations are observed as fluxes that have a minimum and a maximum each day with daily periodicity. The periodic flux has a phase and an amplitude. The diurnal variation is not a time variation in space but is due to the fact that observations are made from the frame of reference of the Earth. Hence, this represents a net drift of the cosmic ray gas with respect to the reference frame of the Earth. One of the causes of diurnal variations is the anisotropy induced due to motion of the Earth in an isotropic cosmic radiation. Low-energy cosmic rays (below
a few tens of GeV) move mostly along the lines of the interplanetary magnetic field. When the solar magnetic field has the best connection with the magnetosphere, there should be a maximum in the cosmic ray intensity. The cosmic ray flux can be decomposed into radial and tangential components. The radial component is compensated by the convective outflow of the solar wind but the tangential component experiences variations. The maximum of such variations are expected to occur around 18:00 local time but maximum intensity occurs a few hours earlier because Earth’s magnetic field bends the flux in tangential direction (references in [87]). The diurnal variations are also influenced by atmospheric conditions, like temperature, humidity, gravity etc. but their effects are negligible compared with the effects of pressure at the location.

**Transient variations**

These variations in the cosmic ray flux are caused by the transient effects in the interplanetary space. In general such variations do not occur at specific periodicities and have different life times. The transient variations are categorized as follows:

**Forbush decreases (FD):** Forbush decreases are characterized by a sudden decrease in the cosmic ray flux intensity followed by a gradual recovery and are world wide in extent. Usually the major portion of decrease is completed within 12-24 hours. The flux has been observed to have a decrease of $\sim 3-20\%$ within a few hours and a recovery lasting from days to weeks [33]. The change in flux is dependent on the rigidity of the particles. Although most of these decreases have a marked onset, smaller but well defined decreases with slower onset times of 2-3 days have also been observed. Forbush decreases have been observed as far as beyond 67 AU. There are several theories for the Forbush type variations and while none of them has been completely supported by observations, a widely accepted cause is enhancement in interplanetary magnetic field due to some solar activity; such an enhancement sweeps the cosmic ray particles away causing a decrease in their flux.
**Ground level enhancements:** Occasionally the Sun accelerated the SEPs to very high energies and such events are observed on the ground as enhanced cosmic ray intensities. The GLEs are characterized by a sudden increase in the cosmic ray flux that is followed by an approximately exponential decay back to the pre-increase level. Increases in cosmic ray flux have been observed to be \( \sim 3\% \) to 4500\% in a few minutes to a few hours followed by a recovery period of a few hours to a day [33]. One of the largest GLEs of the past half century was observed around January 20, 2005, just a month after the culmination of BESS-Polar I flight.

There have been cases where the ground level enhancement occurred around solar maxima and have been observed during the peak of solar activity when the solar magnetic field reverses its sign. While the GLEs occur only about once or twice per year, they can occur any time during a solar cycle.

**Other transients:** Unlike the Forbush decreases and ground level enhancements, which show specific characteristic structures in the cosmic ray intensities, there are transient cosmic ray variations that may not have well defined structures and cannot be classified as a type that has specific known characteristics.

Next a brief discussion is provided on energy dependence of transient variations.

### 3.3 Energy dependence of the cosmic ray modulations

Observations show the cosmic ray variations to be energy dependent as observed through the percent change in intensity and the onset and recovery time scales. The transient variations are mainly observed for cosmic rays of energies 0.1 - 10 GeV.

Gyroradius, \( r \), of a particle in a magnetic field of magnitude \( B \) is given by [33]:

\[
r[AU] = \frac{R[GV]}{45.B[nT]} \tag{3.3.1}
\]
A typical value for B near the Earth is $\sim$ a few nT. Table 3.1 compares the rigidities and gyroradii for protons of various energies, using IMF of the order of $\approx 5$ nT near the Earth. Particles with higher energies have higher rigidities and hence larger gyroradii.

| Energy (proton) | Rigidity (proton) | Gyradius ($|B| = 5$ nT) |
|----------------|-------------------|-------------------------|
| [GeV]          | [GV]              | [AU]                    |
| 0.1            | 0.0004            | 0.004                   |
| 1              | 0.3466            | 0.004                   |
| 2              | 1.7664            | 0.0085                  |
| 5              | 4.9112            | 0.021                   |
| 10             | 9.9559            | 0.043                   |
| 50             | 49.9912           | 0.21                    |
| 100            | 99.9956           | 0.43                    |

Table 3.1: Gyradii of proton at various energies for B = 5 nT.

Therefore, such particles are less affected by the interplanetary magnetic field and undergo less modulation. The local heliospheric conditions during transient phenomena are more complex than a simple rigidity effect because the cosmic ray decreases are highly variable and large anisotropies are present.

### 3.4 Effects of solar activity

Solar activities occurring in the atmosphere of the Sun can modify the characteristics of the solar wind plasma, thus causing variations in cosmic ray intensities. Solar flares and coronal mass ejections (CMEs) are examples of transient solar activity. Solar flares are produced mainly during solar active years but also occur less frequently during the solar quiet years. The coronal mass ejections are bursts of particles rising above the solar corona and heat up the solar wind to tens of millions of degrees. Such transient activities are some of the possible causes for the short-term variations in the cosmic ray intensities.
The short-term cosmic ray modulations we will discuss here are probably results of local (to Earth) physical structures that cause variations and can be identified by characteristics of solar wind magnetic fields, plasma speeds, and other solar wind properties. Hence, it becomes important to explore any correlations between the short term variations in cosmic rays and the characteristics of the solar wind plasma.

### 3.5 Models explaining the transient variations

Several theoretical models have been proposed for cosmic ray decreases and while these models mainly attempt to explain the Forbush decreases, the physics can be applied to any cosmic ray decrease. Lockwood [84] provided a good review of some of these models, especially the Alfvén-Dorman model [15] [31] [103], Dorman model [32], Gold model [77], Parker Blast-wave model [100], Morrison’s model [90] etc.

The galactic cosmic rays are scattered by the interplanetary magnetic field. When there is an enhancement in the IMF, the mean free path of the particles can get reduced causing more scattering and thus a decrease in the cosmic ray intensity. If the Earth is enveloped in a charged particle beam, i.e., in a closed magnetic field structure, the cosmic rays scatter away and their intensity is reduced as measured from the Earth. Turbulent magnetic field can also cause a cosmic ray decrease due to increased scattering.

### 3.6 Summary

In addition to its importance in improving our understanding of the physical processes in the heliosphere, the study of transient variations in cosmic ray intensity has use for the general consumer. During any sudden solar activity, viz., solar flare or coronal mass ejections etc., sudden bursts of high energy charged particles from the Sun into the interplanetary space can potentially affect the space weather conditions around the Earth. Such sudden changes can adversely affect human lives as well as scientific
satellites, military satellites and commercial satellite equipment. Some of the cosmic ray variations have been correlated with geomagnetic storms so understanding the causes of transients will improve our knowledge of such storms. Space weather changes can affect spacecraft and technology on Earth. Good measurements of cosmic ray fluxes are important in improving our understanding of the links between cosmic rays and magnetosphere and heliosphere [52].

The parameters characterizing the heliosphere will be revisited in chapter 7 where I compare observations BESS-Polar I proton data with solar wind properties.

Next chapter discusses the detectors and the measurement technique used in BESS-Polar experiments.
Chapter 4

BESS Program and Instrument

This chapter starts with a summary of overall conditions for the BESS-Polar flights as compared to previous non-polar flights. Then BESS measurement technique is presented, which is followed by brief overview of each detector aboard the BESS-Polar II detector assembly. For each detector, the modifications from BESS-Polar I and the resulting performance improvement are listed. Information on flight preparation and launch is presented at the end.

4.1 BESS-Polar flights

The BESS flights prior to the circumpolar BESS flights were about a day in duration each. This section compares the payload and flight conditions between the BESS-Polar I and BESS-Polar II flights [55]. BESS Polar flights took place in perpetual polar Sun light. Dr. Tetsuya Yoshida and Dr. Koji Yoshimura were managers for the BESS-Polar I and II respectively.

As mentioned in chapter 1, the LDB technique employed in the BESS-Polar flights enabled acquisition of scientific data for \( \sim 10-20 \) days. This provided long enough time frames to observe transient phenomena. Large statistics from these flights allow
detailed probe into observed variations. A brief comparison of BESS-Polar I and II flight conditions is provided in table 4.1.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>BESS-Polar I</th>
<th>BESS-Polar II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch</td>
<td>December 13, 2004</td>
<td>December 23, 2007</td>
</tr>
<tr>
<td>Termination</td>
<td>December 21, 2004</td>
<td>January 21, 2008</td>
</tr>
<tr>
<td>Total float time</td>
<td>8.5 days</td>
<td>29.5 days</td>
</tr>
<tr>
<td>Duration of scientific data acquisition</td>
<td>8.5 days</td>
<td>24.5 days</td>
</tr>
<tr>
<td>Number of events recorded</td>
<td>900 M</td>
<td>4700 M</td>
</tr>
<tr>
<td>Size of data recorded</td>
<td>2.1 TB</td>
<td>13.5 TB</td>
</tr>
<tr>
<td>Instrument trigger rate</td>
<td>1.4 kHz</td>
<td>2.4 - 2.6 kHz</td>
</tr>
<tr>
<td>Fraction of time the instrument was live</td>
<td>0.8</td>
<td>0.77</td>
</tr>
<tr>
<td>Altitude</td>
<td>27 - 39 km</td>
<td>34 - 38 km</td>
</tr>
<tr>
<td>Float depth</td>
<td>4 - 5 g/cm²</td>
<td>4.5 - 8 g/cm²</td>
</tr>
</tbody>
</table>

Table 4.1: An overview of BESS-Polar I and BESS-Polar II flights [55].

The BESS-Polar detector was redesigned from its predecessors, the non-Polar BESS detectors, with the aim of achieving high sensitivity in measurements of low energy protons and antiprotons (< 200 MeV). Hence, the material in the path of a cosmic ray particle was reduced to ~ 5 g/cm². A thin superconducting solenoidal magnet was introduced, and a new detector, the middle time-of-flight (MTOF), was installed for measurements of particles with energies down to ~ 100 MeV. A new tracking system was developed for the cosmic ray particles and a new liquid helium dewar with a longer lifetime was added. The overall instrumentation is similar for both the circumpolar flights. However, based on the performance of the BESS-Polar I instrument, a few improvements were implemented for the BESS-Polar II. These improvements aimed for:

- Higher statistics due to longer cryogenic life-time of magnet (improved not only from BESS to BESS-Polar I but also from BESS-Polar I to BESS-Polar II).
- Unique opportunity to measure low energy flux at solar minimum.
- Lower systematic errors.

The next section explains the measurement technique used in BESS.
4.2 BESS measurement technique

A cosmic ray particle is uniquely identified by its charge (sign and magnitude) and mass. As a cosmic ray particle enters the BESS detector (discussed in detail in the next section), it is deflected by the magnetic field of the solenoid in the detector. The charge and velocity are measured by the time-of-flight system whereas the tracking system measurements provide the mass of the particle. The direction of deflection determines the sign of particle’s charge. The ionization loss of the particle in the detector provides the charge of the particle. The velocity of the particle is derived using the path length of the particle trajectory in the detector and the time-of-flight of the particle. The time-of-flight system measures the hit position of the particle on these detectors. The hit positions are also estimated by reconstruction of the particle trajectory by the particle tracking system. The magnet and tracking detectors determine the particle’s rigidity, which is inversely proportional to the measured curvature of particle’s track. For a particle of mass $m$, charge $Ze$ and velocity $v = \beta c$, and the Lorentz factor $\gamma = 1/(1-\beta^2)^{1/2}$, the rigidity, $R$, is given by

$$R = \frac{p}{Ze} = \frac{\gamma m \beta c}{Ze} \Rightarrow m = \frac{RZe}{\gamma \beta c} \quad (4.2.1)$$

Use of

$$\gamma \beta = \frac{\beta}{(1-\beta^2)^{1/2}} \quad (4.2.2)$$

in 4.2.1 leads to

$$m = \left(\frac{Ze}{c}\right) R \frac{(1-\beta^2)^{1/2}}{\beta} \quad (4.2.3)$$

Equation 4.2.3 implies that the measurement of mass $m$ are affected by:

a. Measurement in $R$

$R$ is obtained by measuring the fitted curvature, $\kappa$, of the reconstructed trajectory.
A particle of higher rigidity deflects less than a particle of lower rigidity in the same magnetic field, i.e.,

\[ R \propto \frac{1}{\kappa} \] (4.2.4)

Thus uncertainty in measurement in \( \kappa \) defines the uncertainty in measurement of \( R \), i.e.,

\[ \frac{\delta R}{R} = \frac{\delta \kappa}{\kappa} \] (4.2.5)

b. **Measurement in \( \beta \)**

The uncertainty in \( \beta \) is given by the uncertainty in position measurement and the uncertainty in time measurement. If the particle traverses a path length \( l \) in time \( t \),

\[ \beta = \frac{l}{ct} \] (4.2.6)

Thus the uncertainty in \( \beta \) is given as

\[ \Rightarrow \frac{\delta \beta}{\beta} = \left[ \left( \frac{\delta l}{l} \right)^2 + \left( \frac{\delta t}{t} \right)^2 \right]^{1/2} \] (4.2.7)

Uncertainties in \( R \) and \( \beta \) provide the uncertainty in the measurement of mass. If \( R \) and \( \beta \) are measured independently, equations 4.2.3 and 4.2.5 give the fractional uncertainty in measurement of mass as

\[ \Rightarrow \frac{\delta m}{m} = \left[ \left( \frac{\delta R}{R} \right)^2 + \frac{1}{(1 - \beta^2)^2} \left( \frac{\delta \beta}{\beta} \right)^2 \right]^{1/2} = \left[ \left( \frac{\delta \kappa}{\kappa} \right)^2 + \frac{1}{(1 - \beta^2)^2} \left( \frac{\delta \beta}{\beta} \right)^2 \right]^{1/2} \] (4.2.8)

BESS carries out redundant measurements of these quantities in order for a more accurate determination of the mass and charge and to reject the particles that interact in the detector. Therefore, a precise identification of the particle is possible over a limited energy range where \( \beta \) can be differentiated from unity.

The next section discusses the BESS detector.
4.3 The BESS detector

Figure 4.1 shows the schematic of the detectors on board BESS-Polar II. The BESS instrument is a sophisticated magnetic-rigidity spectrometer. The detector system is a horizontal, cylindrical arrangement of coaxially placed detector components. A few benefits of the cylindrical configuration are:

a. Optimal geometrical acceptance for a compact detector, which is important for balloon-borne detectors.

b. A strong and uniform magnetic field in the large volume of the detector. This ensures a nearly constant geometrical acceptance for a wide range of momenta and provides high momentum resolution.

c. A large and transparent tracking system inside the solenoid.

d. Uniform detector performance for various hit positions and angles of incidence.

These characteristics are helpful for a reliable determination of the absolute fluxes of the components of the cosmic radiation [88]. From outside to inside, the detector arrangement includes:

a. the outer time-of-flight (TOF) system: this has the upper and lower TOF counters that constitute the outermost detector components,
b. an aerogel Cherenkov counter (ACC), placed between the lower wall of the magnet and the lower TOF,
c. the superconducting solenoid magnet (MAG),
d. a middle time-of-flight (MTOF) detector between the lower IDC and the lower wall of the magnet,
e. the inner drift chamber (IDC): has an upper and a lower IDC, and
f. a jet drift chamber (JET).

In addition, there is a data acquisition system and a solar panel power supply.

As a particle is incident upon the top of the instrument, it traverses the various components of the detector system listed above. The particle passes through, from outside to inside, the upper TOF, the upper wall of the superconducting magnet, the upper IDC, the JET drift chamber, the lower IDC, the MTOF, the lower wall of the magnet, the ACC, and finally, the lower TOF. For the BESS-Polar II detector, the geometrical acceptance varies only a few percent from the lowest detectable energy of \( \sim 100 \text{ MeV} \) to energies up to a few hundred GeV. The magnet is operated at 0.8 T with a maximum magnetic field strength of 1.0 T. The tracking system can fully visualize the incident particle tracks as well as tracks from any other particles produced by interactions inside the detector volume. The detector performance changes very little for various hit positions and angles of incidence. The next few sections describe these detectors in detail.

4.3.1 The outer Time-of-Flight system

The BESS-Polar II Time-of-Flight system consists of an outer time-of-flight (TOF) and a middle time-of-flight (MTOF) detectors. Since most of the instrumentation work I did was focused on the outer time-of-flight system, it is discussed in detail in the next chapter. TOF is the outermost detector system and is comprised of upper (UTOF) and lower (LTOF) time-of-flight detectors formed by cylindrically arranged upper and lower
scintillator layers, respectively. The purpose of this outermost detector system is to provide the instrument trigger and to measure the energy loss of the incident particles to determine their charge and velocity and reject albedo.

4.3.2 The Aerogel Cherenkov Counter (ACC)

The aerogel Cherenkov counter is used as a threshold detector in order to extend identification of heavier particles, proton and helium, to lower energies. A $\pi^\pm$, $\mu^\pm$, $e^\pm$, at the same rigidity as a heavier particle may already be above the Cherenkov threshold and produce a signal in the counter whereas the heavier particle is still below the threshold and does not produce a Cherenkov radiation. Hence, particle identification using the velocity vs. rigidity technique is further improved by the ACC because the light particle background can be rejected, thereby optimizing the identification of heavier particles at low energies. This is essential for separating antiprotons from the very large background of the light negatively charged particles, primarily $e^-$ but also some $\pi^-$ and $\mu^-$. Less difficult but still importantly, it separates protons from $e^+$, $\pi^+$, and $\mu^+$.

Design

The ACC consists of a large light diffusion box containing aerogel blocks, which are viewed by a total of 48 PMTs arranged at both the ends. The weight of the counter and the amount of material in the path of the particle were minimized using a rigid isogrid outer frame and thin carbon-fiber composite windows as light closeouts. The interior of the counter volume is lined with Gore-Tex, which exhibits high reflectivity (> 90 %) even in the short-wavelength region (300 - 400 nm). Hamamatsu R6504, 2.5" fine-mesh PMTs are installed on a single mounting plate on each end of the counter. Based on Monte Carlo simulations, the tilt angle of the mounting plate was set at 31.1° to maximize the effective sensitive area of the PMTs [53]. Table 4.2 summarizes the characteristics of the aerogel blocks used in the ACC for the BESS-Polar I and
BESS-Polar II

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>BESS-Polar I</th>
<th>BESS-Polar II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size of the block</td>
<td>100mm x 100mm x 80mm</td>
<td>190mm x 280mm x 80mm</td>
</tr>
<tr>
<td>Index of refraction</td>
<td>1.02</td>
<td>1.03</td>
</tr>
<tr>
<td>Identification region</td>
<td>( \sim 3.8 \text{ GeV} )</td>
<td>( \sim 3.0 \text{ GeV} )</td>
</tr>
<tr>
<td>Number of blocks</td>
<td>72</td>
<td>12</td>
</tr>
</tbody>
</table>

Table 4.2: Characteristics of the aerogel blocks used in the ACC for the BESS-Polar I and BESS-Polar II.

Why modify from BESS-Polar I?

The reason behind designing a new ACC for BESS-Polar II was to increase the background rejection factor and thereby improve the particle identification over that of the BESS-Polar I. The Polar I ACC did not have enough light yield and hence had a marginal background rejection capability. This caused contamination of the proton and antiproton samples by the residual \( \pi^\pm, e^\pm, \mu^\pm \) backgrounds and resulted in an increased systematic error in the antiproton flux. This would adversely affect the studies of transient variations in intensities of protons. As the number of protons increases, so does the background of \( \pi^+ \) etc. This fraction of increase should be small and similar fractional
changes should be observed in time variation of the proton flux [53]. The geometry of the light diffusion box for BESS-Polar II ACC was optimized for improved light collection by the Monte Carlo simulation using GEANT4 for improved light collection. Particles passing through the interface regions between adjacent aerogel blocks have to be rejected from analysis due to their reduced light yield. The loss of these particles needs to be minimized. This was achieved by using bigger, and hence fewer aerogel blocks to cover the diffusion box for BESS-Polar II ACC. Each block is wrapped in a UV-transparent PET film; larger blocks reduce the amount of absorption in this film. In addition, aerogel blocks with a higher index of refraction, 1.03, were used, whereas that for the BESS-Polar I aerogel block was 1.02. The higher index yields \( \sim 1.5 \) times more light. The aerogel blocks were acquired from Matsushita Electric Works, Japan.

**Performance**

Use of aerogel with higher index of refraction and a reduction in number of particles passing through the interface of aerogel blocks led to an improvement in light yield. The performance of BESS-Polar I and BESS-Polar II are compared in table 4.3.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>BESS-Polar I</th>
<th>BESS-Polar II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of photoelectrons</td>
<td>6.7</td>
<td>11.3</td>
</tr>
<tr>
<td>Rejection power</td>
<td>900</td>
<td>&gt; 10000</td>
</tr>
<tr>
<td>Number of antiproton candidates</td>
<td>1512</td>
<td>&gt; 8000</td>
</tr>
</tbody>
</table>

Table 4.3: Comparison of performance of ACC in BESS-Polar I and BESS-Polar II.

I installed the ACC PMTs in their housings. This task included testing the PMTs before installation, installation of the PMTs in their aluminum housing, then testing the installed PMTs to select PMTs with good performance. During installation of the ACC PMTs in their aluminum housing, it was important that they not be clamped to avoid any damage. The installation of each PMT was an intricate task and was done in small stages of tightening the cover. The applied torque and resulting compression
of the rubber o-ring were measured at several points. William M. Daniels helped me by holding the housing for the last few stages of tightening, he also made the circuit boards for the PMT.

4.3.3 Superconducting Solenoid Magnet

A superconducting solenoid magnet is the core component of the magnetic rigidity spectrometer. As mentioned above, the solenoidal geometry allows the use of a cylindrical configuration and results in a uniform magnetic field in the path of the particles through the detector. The main argument against having a solenoid magnetic configuration is the unavoidable amount of material in the path of a particle. However, the development of an extremely thin superconducting solenoid at KEK for the BESS-Polar flights drastically reduced the amount of material that a particle traverses. This enabled the use of a cylindrical solenoid configuration.

Configuration of the solenoid magnet

The ultra-thin superconducting solenoid coil is 1.4 m long and has a diameter and thickness of 0.9 m and 3.5 mm respectively. It is wound with high-strength aluminum-stabilized NbTi/Cu superconductor (T_c = 10K). This material is as strong as copper so no other cylindrical supporting material was required. A current of 380 A through the solenoid coil produces the maximum magnetic field of 0.8 - 1.0 Tesla with a uniformity of 10 % in the central tracker (JET/IDC). It provides a wall thickness of 0.11 radiation lengths while minimizing incoming particle interaction with the magnet wall material[68]. The magnet incorporated a liquid helium (LHe) reservoir tank (~ 520 L) at one axial end, suspended by a set of support rods from the outer vessel. The coil is indirectly cooled by thermal conduction through pure-aluminum strips and the outer support cylinder linked to this liquid helium reservoir. The high thermal conductivity of aluminum serves to maintain its uniform thermal temperature. The outer vacuum
vessel is made with a honey-comb material to lighten the wall without losing stiffness. This configuration realizes advantages of the minimum wall material in the detector acceptance and also provides an intrinsic safety protection against a magnet quench by suppressing any sudden pressure rise in the reservoir. The amount of material in the coil and its cryostat is 2.46 g/cm$^2$, a vast improvement from the previous BESS spectrometers, which had 4.22 g/cm$^2$ material [54][68].

The coil was successfully tested up to a central magnetic field of 1.0 Tesla and was operated at 0.8 Tesla in the scientific balloon flight. Two-stage radiation shields at $\sim 40$K and $\sim 120$K are used to thermally isolate the coil from the surroundings. In addition, there is a third shield at about 215K. Shields are cooled by the enthalpy of helium gas vapor from the reservoir tank.

**Why modify?**

Since the lifetime of the magnet drives the duration for which scientific observations can take place and the lifetime of magnet during the flight in turn depends on the liquid helium reservoir, the goal of the cryogenic design was to achieve a liquid helium life of longer than 20 days. The following changes in design from BESS-Polar I were
implemented in order to achieve extended lifetime to take advantage of the long duration Polar flights:

(i) larger heat transfer area at a radiation shield cooling line,

(ii) addition of third shield surrounding the liquid helium tank part,

(iii) insertion of high Tc current leads at the cold end of the current leads,

(iv) ~30% increase in tank volume,

(v) longer suspension rods.

As a result, the BESS-Polar II magnet had an operational lifetime of 24.5 days compared to 10 days for BESS-Polar I. Table 4.4 compares the two BESS-Polar magnets. Table 4.5 describes the conductor.

<table>
<thead>
<tr>
<th>Magnet parameters</th>
<th>BESS-Polar I</th>
<th>BESS-Polar II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coil nominal diameter (m)</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Coil length (m)</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td>Coil thickness (center/notch) (mm)</td>
<td>3.4/3.7</td>
<td>3.4/3.7</td>
</tr>
<tr>
<td>Coil weight (kg)</td>
<td>43</td>
<td>43</td>
</tr>
<tr>
<td>Cryostat</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outer dimension (m)</td>
<td>Φ 1.06 x L 3.2</td>
<td>Φ 1.06 x L 3.2</td>
</tr>
<tr>
<td>Inner bore (m)</td>
<td>Φ 0.80</td>
<td>Φ 0.80</td>
</tr>
<tr>
<td>Central magnetic field (T)</td>
<td>0.8 (∼1.0)</td>
<td>0.8 (∼1.0)</td>
</tr>
<tr>
<td>Magnetic uniformity (%)</td>
<td>≤ ±9</td>
<td>≤ ±9</td>
</tr>
<tr>
<td>Current (A)</td>
<td>380 (∼476)</td>
<td>380 (∼476)</td>
</tr>
<tr>
<td>Turns</td>
<td>2829</td>
<td>2829</td>
</tr>
<tr>
<td>Inductance (H)</td>
<td>3.49</td>
<td>3.49</td>
</tr>
<tr>
<td>Stored energy (kJ)</td>
<td>252 (∼395)</td>
<td>252 (∼395)</td>
</tr>
<tr>
<td>E/M ratio in coil (kJ/kg)</td>
<td>5.9 (∼9.2)</td>
<td>5.9 (∼9.2)</td>
</tr>
<tr>
<td>Material @half-wall (g/cm²)</td>
<td>2.52</td>
<td>2.52</td>
</tr>
<tr>
<td>Liquid He capacity (l)</td>
<td>400</td>
<td>520</td>
</tr>
<tr>
<td>Liquid He lifetime (days)</td>
<td>10</td>
<td>21</td>
</tr>
<tr>
<td>Weight of the magnet (kg)</td>
<td>410</td>
<td>450</td>
</tr>
</tbody>
</table>

Table 4.4: Characteristics of the magnet, taken from [68].

The next section provides a brief overview of the middle-time-of-flight detector.
<table>
<thead>
<tr>
<th>Properties of the solenoid conductor</th>
<th>BESS-Polar I and II solenoid</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
<td>Al clad NbTi/Cu monolith</td>
</tr>
<tr>
<td>Overall size with insulation (mm²)</td>
<td>0.9 x 1.2</td>
</tr>
<tr>
<td>NbTi/Cu core diameter (mm)</td>
<td>0.60</td>
</tr>
<tr>
<td>Critical current 2.5T, 4.2K (A)</td>
<td>&gt; 750</td>
</tr>
<tr>
<td>Area ratio (NbTi/Cu/Al)</td>
<td>1.0/0.8/3.9</td>
</tr>
<tr>
<td>Insulation (µm)</td>
<td>Kapton 2 x 20</td>
</tr>
<tr>
<td>Additive into Al stabilizer</td>
<td>Ni (5000 ppm)</td>
</tr>
<tr>
<td>Al clad process</td>
<td>Co-exhaustion</td>
</tr>
<tr>
<td>RRR (Al stabilizer, Cu overall)</td>
<td>286, 55, 116</td>
</tr>
<tr>
<td>Yield strength (NbTi/Cu @RT) (MPa)</td>
<td>580</td>
</tr>
<tr>
<td>Yield strength (Al @4.2K) (MPa)</td>
<td>100</td>
</tr>
<tr>
<td>Yield strength (overall @4.2K) (MPa)</td>
<td>240</td>
</tr>
</tbody>
</table>

Table 4.5: Characteristics of the conductor, taken from [68].

### 4.3.4 The Middle Time-of-Flight Counter (MTOF)

The middle time-of-flight detector (MTOF) is a thin scintillator-array Time-of-Flight hodoscope with fiber readout that enables the efficient detection of low energy (≈ 0.2 GeV) cosmic-rays. Just like other BESS time-of-flight counters, each MTOF counter has a scintillator connected to a PMT on each end through a light guide. The MTOF was first introduced in the BESS experiment for the BESS-Polar I flight. It is installed inside the bore of the solenoid, between the lower walls of the JET and magnet. Its purpose is to provide measurements, in conjunction with the upper TOF, for the lowest energy particles (≈ 100 - 200 MeV) that are stopped at the lower wall of the magnet or that stop in the MTOF itself. This extension to energies below ≈ 200 MeV improves the statistics in the lowest energy band.

**Design**

The Middle TOF consists of 48 plastic scintillator strips with dimensions of 5.6 x 13.3 x 950 mm³. Each end of a scintillator is attached to a lightguide and the other end of the lightguide is connected to a PMT on its other end. Each light guide is a flexible bundle.
of 60 square plastic fibers (1 x 1 mm$^2$). The square fibers allowed their arrangement into a close packed bundle without any gaps. These glued fiber bundles have mechanical strength comparable to that of the solid acrylic light guide but are flexible and hence conform to the complex routing in the narrow space between the JET and the magnet bore. MTOF uses 2.5-inch fine-mesh 8 anode channel multi-anode PMTs, R6504MODX-M8ASSY, from Hamamatsu Photonics. These PMTs are suitable for the small space and their tolerance for the magnetic field. Hence, 8 scintillator strips are connected to a PMT through 8 light guides on each end, forming one module. The MTOF has 6 such modules and uses 12 PMTs, one on each end of a module. For each module, the 8 anode signals are used for determination of charge on a specific scintillator strip and the common dynode signal is used for the timing measurement and indicating a trigger for lower energy particles. The crosstalk between the anodes of the PMT is about 5 - 10 % [36].

**Why modify from BESS-Polar I?**

The MTOF in BESS-Polar I read the signal from only one end of the scintillator. Hence, the timing resolution was poor for particles passing near the far end (away
from the PMT) of the scintillator due to the attenuation of light in the scintillator. This non-uniformity of signal reduced the efficiency of particle identification using the upper TOF and MTOF pair for the time-of-flight measurements. In addition, it must be noted that the three dimensional track of the cosmic ray particle through the detector is reconstructed by the JET/IDC in conjunction with the time-of-flight system where the time-of-flight detector provides the axial position information. The single-end readout MTOF could not determine the axial position of a cosmic ray hit on the scintillator thus impacting the rejection power for background and noise hits. This lower energy region is important because lower energy particles undergo larger short term variations.

The characteristics and performance of the middle time-of-flight for the two BESS-Polar flights are compared in tables 4.6 and 4.7 [36].

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>BESS-Polar I</th>
<th>BESS-Polar II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Readout</td>
<td>single-ended</td>
<td>double-ended</td>
</tr>
<tr>
<td>Scintillator</td>
<td>EJ204, Eljen Technologies</td>
<td>EJ200, Eljen Technologies</td>
</tr>
<tr>
<td>Attenuation length</td>
<td>3.8 mm</td>
<td>1.6 mm</td>
</tr>
<tr>
<td>Pulse width</td>
<td>2.2 ns</td>
<td>2.5 ns</td>
</tr>
<tr>
<td>Form</td>
<td>5.6 mm x 10 mm x 1000 mm</td>
<td>5.6 mm x 13.3 mm x 950 mm</td>
</tr>
<tr>
<td>Number of scintillators</td>
<td>64</td>
<td>48</td>
</tr>
<tr>
<td>Fiber cross section</td>
<td>1 mm x 1 mm</td>
<td>1 mm x 1 mm</td>
</tr>
<tr>
<td>Number of fibers/scintillator strip</td>
<td>36 ( 4 x 9 )</td>
<td>60 ( 5 x 12 )</td>
</tr>
<tr>
<td>Length</td>
<td>500 mm</td>
<td>700/3000 mm</td>
</tr>
</tbody>
</table>

Table 4.6: Characteristics of the MTOF.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>BESS-Polar I</th>
<th>BESS-Polar II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Timing resolution</td>
<td>370 ps @ &lt; 1GeV/c</td>
<td>250 ps @ &lt; 1GeV/c</td>
</tr>
<tr>
<td>Axial position resolution</td>
<td>N/A</td>
<td>34 mm @ &lt; 1GeV/c</td>
</tr>
</tbody>
</table>

Table 4.7: Performance of the MTOF.

Therefore, a more efficient and sophisticated double-ended readout for the MTOF was designed for BESS-Polar II. Trajectory of each detected particle is reconstructed by the BESS tracking system, which is discussed next.
4.3.5 Tracking system: the JET chamber and the inner drift chambers (IDCs)

This system reconstructs the particle trajectory through the BESS detector. The trajectory, or track, provides the radius of curvature of the particle’s path in the magnetic field and is projected into other counters for cross checking measurements of position (e.g. UTOF and LTOF).

**JET and Inner Drift Chambers**

A cylindrical drift chamber, known as a JET chamber, and so called inner drift chamber (IDC) are located inside the warm bore of the solenoidal magnet (figure 4.5). This provides a 3 dimensional “image” of the trajectory of the incident particle through the magnetic field. The JET chamber has a diameter of 0.80 m and is 1.2 m long. It measures the drift time of the particle through the chamber and provides the particle trajectory in the $r$-$\phi$ plane. The trajectory in $z$ direction is determined from the charge division readout on the anode wires.

![Figure 4.5: A schematic view of the JET and IDCs [88].](image)
The sensitive volume of JET is a cylinder of 1 m in length and 620 mm in diameter. It is subdivided into four sections in vertical by horizontal cathode planes made with gold-plated aluminum wires of 200 µm in diameter that are stretched at 4.0 mm interval. A signal wire plane is placed at the center of each section. Each signal wire plane contains equally spaced sense wires alternated with potential wires at intervals of 0.8 mm. Every wire is positioned and fixed by a feed-through that is located in a hole drilled through the end plate. The wire tensions are adjusted and set at half their elastic limits to accommodate the effects of temperature variation and acceleration impact [88].

In order to reduce weight and material, the wall of the cylinder is constructed with a composite panel. This panel consists of a core of thickness 3 mm and two skins that are 0.1 mm thick. The core is made of thermoplastic foam, based on polytherimide (ULTEM 1000). The total material thickness for one panel is 0.12 g/cm². The end plates are made with 25 mm thick GFRP, rigid enough to support a total wire tension of 3.1 kN. To reduce the weight, many recesses of depth 15 mm have been hollowed out in the end plates. The total weight of JET is about 90 kg including two IDCs.

The inner drift chambers (IDCs) are located just inside the cryostat. They provide hit positions in the z-direction with high precision through vernier strip readout and in the azimuthal direction through drift time measurement. These are arc shaped drift chambers with identical double layer structure except for their dimensions. The JET and IDCs share the common end plate. The JET and IDCs are filled with pure CO₂, called ”slow gas” for which the drift velocity at 1 atm. with an electric field of 1 kV/cm is about 7 mm/µs. Due to this slow drift velocity and the small longitudinal diffusion of drift electrons, good spatial resolution and good double-track separation can be achieved using reasonably low power and moderate speed readout electronics. The maximum drift distance of one section in JET is 86.3 mm and the electric field strength in the drift region is about 0.85 kV/cm. This leads to a maximum drift time of 13 µs in the pure CO₂ gas. The number of channels was a compromise between the
required momentum resolution and the total power consumption. In each of the two central (side) sections, 48 (32) sense wires out of 77 (51) are read out at both ends for charge division. Up to 48 points in \( r-\phi \) and in \( z \) are sampled for an incident charged particle traversing the central region of the JET. IDCs were also read out from both ends of each sense wire.

**Measurements with the JET/IDCs**

The transverse and total rigidity of each particle is determined by fitting the three-dimensional hit positions measured by the drift chambers. Energy loss in the chamber gas is also measured using the charge information of the JET. To obtain hit positions in the \( r-\phi \) plane, the drift velocity is calibrated using the flight data. Some tracks have a left-right ambiguity that is lifted by pattern recognition software in the analysis package.

**Measurement of rigidity**: In order to measure the rigidity of an incident cosmic ray particle, first its trajectory through the detector must be reconstructed. Once the track is reconstructed, the rigidity of the particle can be calculated. The \( r-\phi \) fitting provides the transverse rigidity, \( R_T = cB_z/\kappa \) where \( B_z \) is the \( z \)-component of the magnetic field at the closest approach [78]. Then the total rigidity, \( R \), can be calculated as \( R = R_T / \cos \theta \). where \( \theta \) is a dip angle defined as an angle between the total rigidity vector and \( r-\phi \) plane. This \( \cos \theta \) is obtained from the \( z \)-component of the reconstructed 3-dimensional track.

**Measurement of \( z \)-position**: The \( z \) coordinate of a hit position is given by

\[
\frac{z}{L} = \frac{(R + r)Q_b - rQ_a}{R(Q_a + Q_b)}
\]  

(4.3.1)

where, \( z \): hit position,

\( L \): length of the sense wire,

\( R \): resistivity of the sense wire,
R: input impedance of the sense wire,

$Q_a$ and $Q_b$: charges read at the two ends of the hit wire

This provides a first estimation of hit positions along the sense wires of the JET. Then this hit position, in conjunction with the vernier strips of the IDCs, provides a precise measurement of the $z$ coordinate of the hit. The deviations of the measured $\epsilon$ values from the calculated values are translated to the $z$-position resolution [88].

Independent energy loss measurements are obtained from the pulse height measurements of the JET; this helps with particle identification.

The main characteristics of JET and IDC are listed in tables 4.8 and 4.9. The performance of tracking system is summarized in table 4.10.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>BESS-Polar I and II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shape and size</td>
<td>Cylindrical, 690 mm $\phi$ x 1016 mm</td>
</tr>
<tr>
<td>Sense wires</td>
<td>Wire (Au plated), 20 $\mu$m$\phi$, 256 wires</td>
</tr>
<tr>
<td>Wire spacing</td>
<td>8.0 mm (y), staggering of $\pm 300$ $\mu$m (x)</td>
</tr>
<tr>
<td>Potential wires</td>
<td>Al (Au plated), 200 $\mu$m$\phi$, 292 wires</td>
</tr>
<tr>
<td>Wire spacing</td>
<td>8.0 mm</td>
</tr>
<tr>
<td>Cathode wires</td>
<td>Al (Au plated), 200 $\mu$m$\phi$, 465 wires</td>
</tr>
<tr>
<td>Wire spacing</td>
<td>4.0 mm</td>
</tr>
<tr>
<td>Maximum sampling hits</td>
<td>48</td>
</tr>
<tr>
<td>Maximum drift length</td>
<td>86.25 mm</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>140 $\mu$m (x), 4.0 cm (z)</td>
</tr>
<tr>
<td>Maximum detectable rigidity</td>
<td>240 GV/c</td>
</tr>
</tbody>
</table>

Table 4.8: Characteristics of JET.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>BESS-Polar I and II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shape and size</td>
<td>Arc-shaped, $R = 354 - 374$ mm, $</td>
</tr>
<tr>
<td>Sense wires</td>
<td>W/Re (Au plated), 20 $\mu$m$\phi$, 9/8 wires</td>
</tr>
<tr>
<td>Wire spacing</td>
<td>14.0°</td>
</tr>
<tr>
<td>Potential wires</td>
<td>Mo (Au plated), 120 $\mu$m$\phi$</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>150 $\mu$m ($\phi$), 1.0 cm (z)</td>
</tr>
</tbody>
</table>

Table 4.9: Characteristics of IDC.
<table>
<thead>
<tr>
<th>Characteristics</th>
<th>BESS-Polar I</th>
<th>BESS-Polar II</th>
</tr>
</thead>
<tbody>
<tr>
<td>r-φ resolution (JET)</td>
<td>119 µm</td>
<td>116 µm</td>
</tr>
<tr>
<td>Z resolution (JET)</td>
<td>45 mm</td>
<td>25 mm</td>
</tr>
<tr>
<td>Z resolution (IDC)</td>
<td>0.7 mm</td>
<td>0.6 mm</td>
</tr>
</tbody>
</table>

Table 4.10: Performance of the tracking system.

An overview of the electronics is presented in the next section.

4.3.6 Electronics

The outer pressure vessel used in pre-polar flights was eliminated for the BESS-Polar flights in order to minimize the material through which incident particles pass. As a result, the Time-of-Flight Counter and Aerogel Cherenkov Counter as well as related front-end electronics were exposed to ambient pressure during flight. The electronics and Data Acquisition (DAQ) systems were newly developed for BESS-Polar flights to adapt to those conditions.

Why modify from the non-Polar BESS flights?

For the original BESS experiments, standard CAMAC and VME systems were used for the DAQ system. Since the DAQ system in the previous BESS experiments was not fast enough to process all data with an acceptable dead time, BESS was forced to sample data. To obtain this sampling an intelligent second-level trigger system was introduced to remove the large positively charged cosmic ray background in the antimatter search. For the BESS-Polar flights, instead of using any standard bus format, each module was controlled through a serial interface, USB 2.0. A high performance and low power consumption CPU allowed processing of all data without any on board event selection, simplifying the trigger system and reducing the total power consumption. Low-power front-end electronics were developed [59]. A solar panel power system was used to minimize the weight and provide stable power for more than 20 days with a capacity of
900 W. The trigger rate varied from 1.5 kHz to 2.5 kHz and a typical event produced about 2 kBytes of data. More details of the electronics system can be found in [59].

**Tasks carried out by the electronics system**

The signals from various detectors are digitized by the dedicated Front-End Electronics (FEEs). Then the digitized data is sent to the event builder through USB 2.0 signal. The following tasks are carried out [59]:

a. TOF and ACC signals are digitized by the time-to-digital converters (TDC) and the charge-to-digital converters (QDC). The anode signals of the TOF PMTs are used for timing measurement and hence, are connected to the TDC. The signals from dynodes 13 and 18 are used for charge measurement and hence, are connected to the QDC.

b. The drift chamber signals are digitized by the flash analog to digital converter (flash ADC or FADC).

c. The TDC provides input to the trigger board. If there is a coincidence between the UTOF and LTOF or UTOF and MTOF, an instrument trigger, T0, is generated. The trigger board sends the trigger signal together with an 8-bit event number to each FEE to initiate the digitization. The event number is used for the event building process.
d. Once the trigger T0 is generated, the trigger board is locked until it receives a “Ready” signal from all FEEs. As soon as it finishes digitization, each FEE sends the “Read” signal to the trigger board independently. This minimizes the dead time caused by the event processing. Each of the FEEs finishes this process within 50 microseconds, keeping the dead time for the flight under 10%.

e. The data from each FEE is sent to the CompactPCI (cPCI) embedded system individually along with the event number provided by the trigger board. Then an event with this event number is built and the data are recorded to the hard disk drives (HDDs).

f. In order to prepare for the higher trigger rate expected for the BESS-Polar II flight conducted at Solar minimum, each FADC module had a dedicated serial interface so that data throughput rate could be maximized. And at the same time, the CPU board was upgraded to a Core Duo 1.66GHz and the capacity of data storage increased to 16 TBytes from BESS-Polar I.

g. All cosmic ray data that issue triggers during the flight are stored. No event sampling is applied.

4.3.7 Data Acquisition System

The hardware of the Data Acquisition (DAQ) system consists of a commercial CPU board and USB 2.0 Interface cards. The crate was mounted in a pressurized iron vessel which also serves as magnetic shielding to enable operation in the high magnetic field. The software of the DAQ system was developed with C++ code using the ROOT analysis foundation on a Linux operating system. The OS was installed on a Compact Flash. For the BESS-Polar II flight, the Scientific Linux 5 with kernel 2.6 was used. See [59] for more details.
4.3.8 The Control and Monitor Subsystems

During the flight, the spectrometer was controlled and monitored from the ground through telemetry. Figure 4.7 shows a block diagram of the communication flow. The PC104 system was used both at the ground station and on board the payload. By connecting the ground PC to the PC104 flight system through ethernet, similar operating conditions except for telemetry communication could be provided during testing on the ground [59].

4.3.9 Power System

Solar power

A solar battery system provides electrical power to the front-end electronics and data acquisition system. This takes advantage of the fact that during the Antarctic summer, when the BESS-Polar flights took place, the Sunlight is available 24 hours a day. The previous, non-Polar, BESS flights used lithium batteries as primary source of electricity, but they are too heavy to be used for long duration flights where power is required for several days. BESS-Polar II had 90 solar panels mounted on an omni-directional...
octagonal frame around the payload, and no mechanism was used to point the solar panels towards Sun. The solar panel was designed to provide 450 W of electrical power throughout the flight.
Backup batteries

While an efficient solar panel system is used, a set of batteries was installed as a backup in case of any loss of solar power or accident resulting in shock during the flight. These are non-rechargeable primary lithium batteries and can provide power to the BESS-Polar detector for \( \sim 12 \) hours. These batteries have high continuous current capability of 3A, provide a stable output of \( \sim 2.8\)V and can operate over a wide range of temperature range from -40C to 85C.

DC-DC converter

The power from the solar cells is regulated by a DC-DC converter system located inside the payload. This system consists of a converter of type VICOR VI-J series with an efficiency of \( \sim 70\text{-}80\% \). It is installed as far away from the solenoid as possible, because the DC-DC converter is strongly affected by the magnetic field due to the induced EMF. The magnetic field near the DC-DC converter was \( \sim 70\) G. This converted power is then fed to the power bus lines of the electronic crates [88].

4.4 Payload preparation and launch

After fabrication and individual testing of each component of the BESS-Polar II spectrometer, all detectors were mounted on the spectrometer. Prior to the balloon flight, the instrument was tested again in Antarctica.

Payload integration and compatibility test

The payload integration was carried out from July 26, 2007 - August 27, 2007 at Columbia Scientific Balloon Facility, Palestine, TX. The payload was integrated with the solar battery system. This was followed by a compatibility test of the payload with the ballooning system mechanical attachment and communication between the payload
and satellite. Upon successful completion of the compatibility test, the BESS-Polar II payload was granted permission to be launched from McMurdo Station, Antarctica.

**Flight preparation and launch, Antarctica**

After the compatibility test the payload was shipped to Antarctica. The payload and the BESS-Polar team flew to McMurdo Station, Antarctica on the same plane from Christchurch, New Zealand to arrive at McMurdo station, Antarctica on October 26, 2007. The components of the spectrometer were further tested individually and together regularly at Williams Field near McMurdo station. The payload underwent another compatibility test on November 27, 2007 before it was pronounced fit for launch. The payload was wrapped in aluminized mylar to protect the system from the heat generated by Sunlight while it would be afloat. While waiting for the day of its launch the payload was constantly monitored and tested. The BESS-Polar II payload was launched on December 23, 2007 from Williams Field and then was monitored from Crary Lab at McMurdo station for data acquisition and functioning of components.
A successful data acquisition was carried out until the liquid helium for cryogen was exhausted and the data storage capacity was full. After that the scientific operation was turned off and the team waited for the payload to float back to near McMurdo station before terminating it for a relatively easy retrieval. However, the payload got stuck and there seemed to be little possibility for it to float back to near McMurdo Station before the summer was over so the flight was terminated and the payload landed in Patriot Hills near the WAIS Divide (West Antarctic Ice Sheet). The data vessel was retrieved from the site by Ms Anne DalVera and Mr. Phil Austin of the Raytheon Polar Services. The rest of the payload was left behind because the flight termination occurred towards the end of summer season and there were not enough recovery flights available to retrieve the payload. The BESS-Polar team returned to Antarctica and retrieved the payload in January 2010. The recovery camp was managed by Anne DalVera and support services were provided by Megan Walker. In February 2011 the BESS team announced the magnet had been successfully recharged.

4.5 Summary

BESS-Polar I and II were successful long duration balloon flights. The detectors performed well on both but the overall performance was improved in BESS-Polar II flight. Data from both flights will be useful in study of transient variations of cosmic rays.

The next chapter provides details of design and fabrication of the outer time-of-flight detector system.
Chapter 5

The Time-of-Flight System for BESS-Polar II

This chapter discusses the purpose of the outer time-of-flight detectors (TOF) and the physics behind the measurements carried out by the TOF. Details of design and fabrication of the TOF are provided because my participation in instrumentation focused on those areas. This is followed by experimental conditions and performance of the TOF during the BESS-Polar II flight. Because calibration of the TOF was carried out by K. Sakai and M. Sasaki, only results of calibration are given.

5.1 Time-of-flight detectors

The purpose of the outermost detector system, TOF, is to provide the instrument trigger, measure the charge and velocity of the incident particles, and reject albedo.

TOF consists of two arrays of long, narrow and thin plastic scintillator\(^1\) paddles, one above (the upper TOF or the UTOF) and one below (the lower TOF or the LTOF) the other instrument elements. Due to the absence of any outer pressure vessel, the TOF

\(^1\)A scintillator is a material that produces a pulse of light upon passage of a charged particle [71].
operated in the ambient environment and was designed to address the effects of exposure to stray Sunlight, thermal expansion/contraction, and the low pressure environment.

The main purposes of the TOF are discussed in the next section.

5.2 Main purposes of the TOF

For each incident cosmic ray particle that triggers the detector, the TOF directly measures two quantities, namely, the time when the particle hit the scintillator (the hit time) and the number of photons produced from the ionization loss of the particle in the scintillator. The energy deposited in the UTOF and LTOF is determined by measuring the amount of light emitted by the ionization loss of the incident charge particle in the scintillator. Then the charge of a particle is determined from the energy deposited in the UTOF and LTOF. The measurement of time of arrival of the particle by the TOF, in conjunction with the track reconstruction information from the JET chamber, provides the velocity of the particle. The LTOF has the lowest detectable energy of $\sim 0.15$ GeV, while the MTOF can detect particles that have energies down to $\sim 0.10$ GeV at the top of the atmosphere.

The next section discusses these purposes.

5.2.1 Measurement of ionization loss

This section starts with the principle of ionization loss and then discusses how this measurement is carried out by the TOF.

Principle of ionization loss

As a high energy particle passes through a solid, liquid, or gas, it can have considerable effect on the constituent atoms, molecules, and nuclei. The three basic processes that can occur are [85]:

63
(i) Ionization and excitation of the atoms and the molecules of the material. This process is known as ionization loss process. The electrons are torn off the atoms by the electrostatic forces between the incident high energy particle and the electrons of the atoms in the material. This also causes heating of the material due to the transfer of kinetic energy to the electrons.

(ii) The destruction of the crystal structures and molecular chains of the material.

(iii) Nuclear interactions between the high energy particles and the nuclei of the atoms of the material.

Here we focus on the ionization losses because this process dominates the response of the BESS TOF detectors. The ionization loss in a detector can be used to measure the particle flux and other properties. Note that under cosmic conditions the ionization loss influences the propagation of high energy particles and provides an effective mechanism for heating interstellar clouds.

For a relativistic particle with velocity \( \beta \) (Lorentz factor \( \gamma \)), the ionization loss is given by the Bethe-Bloch formula; it provides the total energy loss per unit length and, in its general form, can be written as:

\[
dE/dx \propto \left( \frac{Z}{\beta} \right)^2 \left[ \ln \frac{2m_e c^2 \beta^2 \gamma^2}{I} - \beta^2 - \frac{\delta(\gamma)}{2} \right]
\]

(5.2.1)

where,

\( dE/dx \) is the energy loss per unit length, as the particle traverses length \( x \).

\( Ze \) is the charge of the incident high energy particle.

\( m_e \) is the mass of an electron.

\( \delta(\gamma) \) is a correction for the density effect which is discussed below.

\( I \) is the mean ionization potential of the atoms in the material.

Because there are electrons at different energy levels from which they can be ejected, the formula is derived using a weighted mean of all states of the electrons in the atom.
Eq. 5.2.1 shows that the ionization loss depends only on the velocity and charge of the incident particle; there is no dependence on its mass. The ionization loss dependence on the material is linear through the electron density factor and logarithmic through the mean ionization potential. The mean ionization potential per electron depends on the atomic number of the atom [71].

Extreme atomic shell corrections are necessary at very low $\beta$ when the velocities of the incident particle and the characteristic orbital velocity of bound electron become comparable. At very high $\gamma$, corrections for kinematic and incident particle structure may be necessary.

As the velocity of the incident particle, which is a representative of its energy, increases from near the energies of the bound electron, $dE/dx$ decreases as $1/\beta^2$. The ionization loss is minimum for kinetic energies $E \approx Mc^2$. As $\beta$ approaches 1, the $\ln \gamma^2$ in eq. 5.2.1 begins to dominate and the $dE/dx$ starts to increase. This region is known as the region of relativistic rise. The relativistic rise does not continue indefinitely as encompassed in the term $\delta(\gamma)$. This is due to the fact that the incident particle does not interact with a single atom in the material but in a dense material, where interatomic spacing is small, several atoms may be enclosed within the allowed impact parameter. Hence, the interaction between the electrons of these atoms may screen the electric field of the projectile resulting in a reduction of ionization loss for distant collisions. This is the density effect and it causes the energy loss in the region of relativistic rise to increase as $\ln \gamma$ (instead of $\ln \gamma^2$) when the collision term is split into near and distant encounters, and eventually the ionization loss becomes constant at a very large $\gamma$. This region is known as the Fermi plateau.

It is clear from eq. 5.2.1 that for two particles of same $\beta$ but different charges, the ionization loss in the material depends only on their charges. Hence, if $\beta$ is measured independently, the eq. 5.2.1 determines the charge of the incident particle.
Here it is important to note that since $\beta \approx 1$ for the particles that are of interest to us in the BESS experiment, the measurement of $dE/dx$ allows us to uniquely identify the charge of the incident particle.

**Ionization loss and charge measurement in BESS**

The energy loss due to interaction of an incident particle in the scintillator may be enough to ionize the atom or may excite the electrons to a higher level from which the electron may come down to a lower energy level and produce a photon. Number of photons generated depends on the energy of the incident particle and the thickness of the material it traverses in the scintillator. Hence, the number of generated photons is an indicator of the ionization loss of the particle in the scintillator. These photons travel to the PMT attached at the end of the scintillator. These photons hit the photocathode of the PMT where photoelectrons are emitted. The number of photoelectrons depends on the quantum efficiency of the PMT. These photoelectrons, which travel towards the anode of the PMT, are amplified by the stages of dynodes in the PMT and are eventually collected at the anode.

However, not all the photons generated in this manner reach the PMTs, because they are attenuated during their travel to the PMT. Some light is also lost when photons escape if they hit the edge of the paddle at an angle of incidence $< \theta_{\text{critical}}$. Some of this escaped light is reflected back from the scintillator wrapping. Thus the number of photons reaching the PMT is always smaller than the actual number of photons generated by the incident cosmic ray particle.

In the BESS-Polar experiment, the QDC (charge to digital converter) data are normalized for the gains of the PMTs and the QDCs after subtracting the pedestals which indicate zero signal. The $dE/dx$ in the scintillator is obtained by averaging the signals for each PMT on the two ends of that scintillator. In order to calculate this average, two factors are important; the length the particle traverses in the scintillator and the
attenuation of light in the scintillator. The traverse length determines the amount of interaction of the particle with the scintillator atoms resulting in photons, whereas the attenuation of light is indicative of actually how much light will reach the PMTs to be recorded. This average signal is calculated by dividing the signal by the traverse length in the scintillator and applying the correction for attenuation of light in the scintillator [78][123].

In the real world, the emitted light is not linear with energy loss. Corrections also need to be made for loss of light in the scintillator. The measured charge shows dependence on the position of the hit of incident particle on the scintillator. This because the longer the generated photons travel, the higher the attenuation of the light in the scintillator is. In BESS-Polar measurements, the $z$-dependence ($z$ is along the length of the scintillator) affects the measured charge as: Then the charge measured $\propto a + b e^{cz}$ where, the parameters $a$, $b$, and $c$ are determined by calibration of the instruments. Hence, the steps taken for dE/dx measurements are [123]:

1. Subtract the pedestal value from the measured charge obtained from QDC for each PMT.
2. Normalize this QDC data for the gains of PMT and the QDC.
3. Correct the signal amplitude for the attenuation of light as it traverses from the hit point to the PMT.
4. Average the corrected charge from the PMTs on both ends of a paddle.
5. Divide the averaged charge by the length of the path the particle traverses in the scintillator. This provides the dE/dx measurement in the TOF counter. This dE/dx is then normalized such that the mean value of the dE/dx distribution is unity for minimum ionizing particles.

Figure 5.1 shows scatter plots of dE/dx vs. rigidity of the particles, measured for the UTOF and LTOF. The rigidity is calculated from the curvature of the particle’s track through the BESS-Polar detector.
5.2.2 Timing Measurement

The time-of-flight of a particle through a detector assembly is the time duration between the moments the particle enters one detector (UTOF) and leaves another detector (e.g. MTOF or LTOF). For this discussion, the time-of-flight is the time in which the particle traverses the detector from the UTOF to the LTOF.

In order for its time-of-flight to be determined, a particle must pass through a UTOF paddle and an LTOF paddle. As the particle hits the paddle in the UTOF, its presence is recorded by the PMTs on both the ends of that paddle. Each PMT records the hit time as measured by the TDC and the measured integrated charge of the signal produced in the PMT. Similar measurements are made by the PMTs of the LTOF paddle that is hit by this particle at the end of its trajectory through the detector. The following treatment of timing measurement follows the method described by Shikaze et al. [17].

Principle of timing measurement

Here we must note that the time measured by the TDC is not the actual time when the particle hit the TOF paddle but includes some additional time because the light
takes some time to travel from the hit position to the PMT faceplate and the time-walk effect of the PMT caused by the time jitter of the PMT signal. Hence, the time-walk corrected hit time, $t_c$, can be expressed as

$$t_c = t_i - W_i / \sqrt{q_i}$$ \hspace{1cm} (5.2.2)

Where, $t_i$ : time measured by the TDC
$q_i$ : integrated charge of the PMT signal, and
$W_i$: a correction parameter obtained by fitting the data

Consider the following diagram for the path of a particle through the detector

Let us consider a particle that hits the upper TOF paddle at $z = z_u$ position and the lower TOF paddle at $z = z_l$ position where the center of the counter is at $z = 0$. Suppose $T_{1u}(z)$, $T_{2u}(z)$, $T_{1l}(z)$, and $T_{2l}(z)$ are the hit times for PMTs on ends 1 and 2 for the upper and lower counters respectively, $L$ is the length of the counter paddle including the light guide, $V_{eff}$ is the effective speed of light in the scintillator, and $T_{ref}$ is the reference time. Then
\[ T_{1u}(z) = t_{1uc} - \frac{L/2 - z_u}{V_{eff}} - T_{ref} \] (5.2.3)

\[ T_{2u}(z) = t_{2uc} - \frac{L/2 + z_u}{V_{eff}} - T_{ref} \] (5.2.4)

\[ T_{1l}(z) = t_{1lc} - \frac{L/2 - z_l}{V_{eff}} - T_{ref} \] (5.2.5)

\[ T_{2l}(z) = t_{2lc} - \frac{L/2 + z_l}{V_{eff}} - T_{ref} \] (5.2.6)

Then the time-of-flight of the particle, \( T_{tof} \), is given by the

\[
\text{Difference} - \text{of} - \text{Sum(DS)} = \frac{(T_{1l} + T_{2l}) - (T_{1u} + T_{2u})}{2} \tag{5.2.7}
\]

If the measured rms of \( T_{1u}(z) \) and \( T_{2u}(z) \) are denoted as \( \sigma_{1u} \) and \( \sigma_{2u} \) respectively, the weighted average of the hit time measurement at the upper TOF is given by

\[ T_{wa,u}(z) = \frac{T_{1u}(z)/\sigma_{1u}^2 + T_{2u}(z)/\sigma_{2u}^2}{1/\sigma_{1u}^2 + 1/\sigma_{2u}^2} \] (5.2.8)

Similarly, for the lower TOF

\[ T_{wa,l}(z) = \frac{T_{1l}(z)/\sigma_{1l}^2 + T_{2u}(z)/\sigma_{2l}^2}{1/\sigma_{1l}^2 + 1/\sigma_{2l}^2} \] (5.2.9)

The time-of-flight, \( T_{tof} \), is then calculated as

\[ T_{tof}(z) = T_{wa,l}(z) - T_{wa,u}(z) \tag{5.2.10} \]
Here it is important to note that the choice of $T_{ref}$ has no effect on the calculation of the $T_{tof}$ because it cancels during the subtraction.

**Timing resolution**

The particle velocity and hence its time-of-flight between the upper and lower counters is also a function of the track inclination as determined by the track reconstruction in the JET chamber. The time-of-flight from the tracker is given by

$$T_{trk} = \frac{L}{c \beta_{trk}(R, M)} = \frac{L}{c} \frac{E}{p} = \frac{L}{c} \sqrt{\frac{((ZR)^2 + (Mc)^2)}{(ZR)^2}}$$  \hspace{1cm} (5.2.11)

Where,

- $L$: length of the path of the particle, determined from track reconstruction
- $c$: speed of light
- $\beta_{trk}$: velocity of the particle as determined from the track reconstruction
- $R$: rigidity of the incident particle
- $M$ and $p$: mass and momentum of the incident particle, respectively
- $Ze$: charge of the incident particle

The timing resolution in the TOF is given by

$$\Delta T = T_{tof} - T_{trk}$$  \hspace{1cm} (5.2.12)

At energies where $\beta < 1$, the error in measurement of $R$ is very small resulting in a negligibly small error in $T_{trk}$. Hence, we take the rms of $\Delta T$ to represent the timing resolution for the TOF.

Once the $\beta$ of the incident particle is known, its mass can be calculated using eq. 4.2.3.

The next section described how the TOF applies instrument trigger.
5.2.3 Application of instrument trigger

For each PMT the anode signal is used for timing measurement and the signals for dynodes 13 and 18 are used for the measurement of dE/dx. Dynode 13 signals (with less gain than anode signals) are specifically useful for highly charged particles because such particles generate large signals and can cause the saturation of anode signal. The capacitors after the 13th dynode reduce the cross-talk of the 13th dynode. The cross talk is affected by the large charge cascading towards anode from dynode 13 [17].

The anode signal is connected to a TDC (time to digital converter) which also provides a signal to trigger the instrument. An instrument trigger, T0, is generated by the trigger electronics when there is a coincidence of hits on the UTOF and on the LTOF or MTOF detectors. The trigger electronics receives the discriminator outputs from the TDC boards, generates a T0 trigger based on a programmable coincidence and distributes the T0 trigger to all Front End Electronics (FEEs). A periodic T0 trigger is also issued by an internal clock to evaluate the performance of FEEs during the flight. Since each FEE sends the data to the event builder independently, the trigger board creates and distributes an 8-bit event number to synchronize all the data segments of an event. The trigger board electronics sends the trigger signal along with an 8-bit event number to each FEE to initiate the digitization.

Design and fabrication details of the TOF are discussed in the next section.

5.3 Design of the TOF

As mentioned earlier, the outer Time-of-Flight system is comprised of an upper and a lower scintillator counter. These two TOF layers are cylindrical surfaces located approximately 0.75 meter from the center of the magnet. The upper and lower TOF layers are comprised of 10 and 12 closed-paced scintillator paddles, respectively. Each TOF paddle contains a scintillator, two light guides, two adapter disks and two photomultiplier
tubes (PMT). Since there have been significant changes from the TOF for BESS-Polar I, the detector is described here. A light guide is glued on each end of the scintillator.

Figure 5.3: The anatomy of a BESS-Polar II TOF paddle (PMTs not shown here).

A circular ultraviolet transmitting (UVT) acrylic disk is glued on each light guide and is used as the adapter disk between the light guide and the PMT. This adapter disk fills the gap between the light guide and the PMT faceplate, which is slightly recessed due to its aluminum housing. Before gluing the PMTs to the light guides through the adapter disks, the paddle is wrapped in aluminized kapton followed by two layers of wrapping in tedlar. The purpose of the kapton is to reflect escaping light back into the paddle in order to minimize loss of photons. The purpose of the tedlar is to disallow any ambient light from entering the paddle and distorting the signal. The outcome is a paddle that has been optimized for maximum light collection by PMTs with no penetration by any outside light.

The scintillator material is Eljen Technologies' EJ-204 cast to 1.2 cm thickness (1.0 cm for BESS-Polar I). Each paddle is diamond milled to an overall width of 10 cm and a length of 95 cm. The edges along each scintillator have been beveled to accommodate close packing on the cylindrical support frame and provide contiguous scintillator coverage of the respective TOF layers.

Two UVT acrylic light guides are glued to scintillator with optical cement (EJ-500). The light guides are diamond milled from cast UVT acrylic stock with a nominal thickness of 1.2 cm and a length of 27 cm. The light guide positions the PMT such that the stray field of the magnet is axially aligned with the fine-mesh PMT. The width of the
Figure 5.4: Cross section view of paddle arrangement in UTOF (top) and LTOF (bottom), showing the level of packing. Only three paddles are shown here.

Figure 5.5: Example: Side view of paddles in the UTOF and LTOF.

Light guide is slightly smaller than that of the scintillator, to avoid potential interference of adjacent light guides and to allow the scintillators define the near contiguous surface in the TOF. The shape of the light guide is optimized for light collection and time resolution using a Monte Carlo computer simulation. The surface of the light guide that is opposite to the side where the PMT is attached is slightly tapered to improve the light collection.
5.3.1 Factors that affected the design of TOF

Several factors affected the design and assembly of the TOF. The TOF PMTs are in a \( \sim 0.150 \) Tesla magnetic field but any magnetic shielding is disfavored due to the weight constraints. The Hamamatsu R6504 2.5\" fine mesh PMTs were selected because they can tolerate magnetic fields of such levels if the field lines are parallel to the axis of the PMT [65]. To achieve this magnetic field alignment, the TOF PMTs are attached such that the faceplate of the PMT is glued to the surface of the light guide making the PMT normal to the surface of the light guide rather than head on. Due to the cylindrical symmetry, the magnetic field is parallel to the axis of all the PMTs with this orientation. The angle between the PMT axis and magnetic field lines is \(<16\) degrees.

The alignment is described in figure 5.6 [17]. The light guide surface opposite to the PMT is tapered to improve the light collection. The shape of the light guide is optimized for light collection and time resolution using a Monte Carlo computer simulation.

As mentioned earlier, the outer pressure vessel used in previous BESS experiments was eliminated and the outer most detector systems, including the TOF, operated in ambient flight conditions. Therefore, the outer detector was designed to address the
effects of exposure to the stray Sun light, thermal expansion/contraction, and the low pressure environment. The latter is particularly important with respect to coronal discharge on the high voltage (HV) components of the PMT.

In the BESS-Polar I experiment, the potted PMT assemblies, provided by the manufacturer for the TOF, had a high failure rate when exposed simultaneously to low pressure and low temperature. Consequently, only 60% of the outer TOF PMTs were operational in BESS-Polar I. To improve the reliability of the TOF PMTs for the BESS-Polar II flight, hermetic aluminum PMT housings, developed at NASA/GSFC, were adopted. Such hermetic housings had been successfully used in the BESS-Polar I ACC. In addition, a hermetic housing is $\sim 50\text{g}$ lighter than a potted one. Before its selection for the flight, each TOF PMT underwent a thermal vacuum environmental test.

To maintain atmospheric pressure inside each PMT housing, the PMT face plate is pressed against a gasket flange on the aluminum PMT shell. The optical coupling between the recessed PMT face plate and the light guide is provided by a UV transparent acrylic disk, which is glued with optical RTV on both sides. The PMT light guide holder has been designed to provide mechanical support of the PMT and act as the light barrier for ambient light. The light guide holder is shown below in figure 5.7(a) and 5.7(b) before and after the installation of the PMT.

The next section describes how the paddles were selected for the TOF.

5.3.2 TOF paddle selection

The scintillators and light guides were graded based on their actual dimensions relative to the optimal dimensions, any manufacturing defects etc. The PMTs were selected after testing for the trigger rates, noise, afterpulse rates, and very importantly based on the pressure and thermal testing after they were installed in their aluminum housing. An afterpulse is essentially a “false” signal generated within the detector itself. Inside a PMT, a photoelectron traveling towards the anode can escape the dynode and then
ionize the residual gas within the vacuum. If the gas ion hits the photocathode, the photocathode will emit an electron that will then be pulled back within the dynodes and multiplied, creating the afterpulse. The combination of the best scintillators, light guides and PMTs were used to make the paddles for the central part of the TOF and the least good paddles were installed on the edges, both for the UTOF and the LTOF.

The assembled TOF paddles are mounted on a thin carbon fiber support shell which is glued to a surrounding aluminum support frame minimizing the amount of material seen by the particle. To allow for differential thermal expansion, both ends of each TOF paddle is allowed to move in the longitudinal direction.

The upper and lower TOF counters are shown in figure 5.9.

The next section provides details on how the TOF data are used for measurements of charge and hit time for a recorded cosmic ray event.
Figure 5.8: Thin carbon fiber support shell. The paddles are be mounted on top of the Tivek to allow thermal contraction/expansion while avoiding any damage to the paddles during the movement.

5.4 Measurement of physical quantities from the TOF data

Signals from dynodes 13 and 18, and anode provide charge and timing measurements as follows:
5.4.1 Charge measurements

If QDC data of both PMTs on a TOF counter are available, the charge deposited on the TOF is calculated from

\[
\text{Charge deposited in TOF} = \sqrt{\left( \frac{\text{QDC of PMT1}}{\text{QDC gain}} \right) \left( \frac{\text{QDC of PMT2}}{\text{QDC gain}} \right) \frac{\text{path length}}{\text{path length}}} \tag{5.4.1}
\]
If QDC data of only single PMT are available, the total charge deposited in that TOF counter is calculated using an attenuation function of track Z position. In this case

\[
\text{Charge deposited in TOF} = \frac{q_{\text{dc of PMT}}}{(\text{attenuation factor})(\text{path length correction factor})} \tag{5.4.2}
\]

If energy loss is larger than dynode18 full scale, or dynode 18 QDC data is not valid, dynode13 QDC is used.

5.4.2 Hit time measurements

The hit time recorded by a PMT is obtained as:

\[
\text{hit time} = (TDC \text{ value})(TDC \text{ clock}) - (TDC \text{ offset}) \tag{5.4.3}
\]

If the TDC data are available for both the PMTs in a TOF counter, the hit time is obtained as the average of the hit time at each PMT. If the TDC data are available only for one PMT then this measurement, combined with the z position measurement from the track reconstruction provides the hit time as follows:

\[
\text{hit time} = (\text{hit time measured by the PMT}) + \frac{(z \text{ position of track})}{(\text{propagation velocity of light in the material})} \tag{5.4.4}
\]

A description of the high voltage for the TOF PMTs is provided next.

5.5 HV setting for the TOF PMTs during the flight

Individual PMTs were tested before and after they were installed in their aluminum housings. After their installation into the housings, the assembly underwent thorough thermal and pressure testing. They were tested again for their performance with the
application of high voltage and voltage-gain curves were derived for all of the PMTs. Each TOF counter went through rigorous testing for the performance as well as to ensure that there was no light leaking into the counter through the wrapping. The original plan was to apply the HV for PMTs such that all PMTs were set at the same gain. However, upon further testing of the system after the UTOF and LTOF were installed on the BESS-Polar II instrument, it was clear that PMTs showed different gains as a result of combination of optics and performance of each individual scintillator paddles. Hence, more data were obtained with the instrument as a whole during the flight compatibility test in Palestine, TX (July 26 - August 29, 2007) and later during the preparations for another compatibility test in Williams Field near Mc Murdo Station, Antarctica (November 2007). For the BESS-Polar II flight the HV for each PMT was set so as to ensure that all TOF counter PMTs had same QDC value.

The next section summarizes performance of the BESS-Polar TOF.

5.6 Performance of the TOF

Figure 5.10 shows the particle ID for singly charged particles with positive rigidity. Figure 5.11 shows the time resolution for a combination of upper and lower TOF paddle. For this combination a time resolution of better than 120 ps is achieved for BESS-Polar II. Preliminary tests on the full data set show that the reported performance of the TOF and other systems is valid for the entire flight. During the flight the monitor data for two of the PMTs were not true representatives of their conditions. It is quite possible that the PMTs were working well but we turned those two PMTs off to avoid any future degradation. In addition, a few PMTs became noisy. The height of the noise pulses were found to be relatively small compared with that of the cosmic-ray signals. However, any possibility of degradation of the TOF performance was avoided by slightly raising the discriminator threshold for these noisy PMTs.
Figure 5.10: Particle identification for singly, positively, charged particles.

Figure 5.11: Time resolution of outer TOF system (from K. Sakai).
The following table shows a comparison between the BESS-Polar I and BESS-Polar II TOF systems:

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>BESS-Polar I</th>
<th>BESS-Polar II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scintillator dimensions (LxWxT)</td>
<td>94.5 cm x 10 cm x 1 cm</td>
<td>96 cm x 10 cm x 1.2 cm</td>
</tr>
<tr>
<td>Light guide dimensions (LxT)</td>
<td>Mitsubishi Rayon</td>
<td>Eljen UVT acrylic</td>
</tr>
<tr>
<td>Light guide material</td>
<td>None</td>
<td>UVT acrylic</td>
</tr>
<tr>
<td>Adapter disk</td>
<td>Potted assembly</td>
<td>Hermetic aluminum housing</td>
</tr>
<tr>
<td>PMT housing</td>
<td>170 ps</td>
<td>120 ps</td>
</tr>
<tr>
<td>Timing resolution</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.1: Performance of the TOF system.

5.7 Summary

A state of the art time-of-flight system was built which performed as designed. The use of aluminum hermetic housings for the PMTs was successful and resulted in stable HV and performance for all the PMTs. This was a marked improvement from the BESS-Polar I TOF PMTs, which used potted PMT assemblies from the manufacturer. Including the cable and support frame, the UTOF and LTOF weighed \(\sim53\text{kg}\) and \(\sim63\text{kg}\) respectively in comparison to \(\sim55\text{kg}\) and \(\sim65\text{kg}\) for those in the BESS-Polar I TOF. The other changes from the BESS-Polar I TOF include the increase in the thickness of the scintillator by 20% and the use of adapter disk between the light guide and the PMT, which was necessary due to the design of the housing assembly, in order to maximize the collection of photons. These changes led to an improved timing resolution of 120 ps for the outer TOF as compared to 170 ps for BESS-Polar I TOF. The hermetic housings for the TOF PMTs performed very well without high voltage breakdown and ensured BESS’ large aperture. The upper and lower TOF have a total of 22 paddles with a total of 44 PMTs. While the PMTs for the TOF were installed at KEK, Japan by Yosuke Matsukawa, I installed the 48 PMTs used in the Aerogel Cherenkov Counter at NASA/GSFC.
BESS is a large and complex instrument involving many scientists, engineers, and students. Everyone is part of the team. Except where noted, the work described in this chapter was done by the candidate under the guidance of Dr. Thomas Hams, Dr. John W. Mitchell and Dr. Robert E. Streitmatter of NASA/Goddard Space Flight Center, Greenbelt, MD. Gluing the light guide and scintillator, gluing of the PMTs on the paddles, scintillators etc. were tedious procedures; I worked with Thomas on this. I was responsible for polishing the scintillators and reflective wrapping of the scintillator paddles. The tedlar wrapping was carried out with David Jackman. The cutouts for appropriate shapes of the wrapping material for the lightguides were designed and fabricated by Francisco San Sebastian. In addition to his help with some mechanical aspects, Donald P. Righter helped me with application of RTV on the aluminum frames used to attach PMTs to the paddle.

The next chapter presents the data analysis carried out to explore proton fluxes for time variations.
Chapter 6

Data Analysis

This chapter describes the process of data analysis and results for the study in this dissertation. The main purpose is to explore the cosmic ray proton data from BESS-Polar I for temporal variations. BESS-Polar data set includes particles for various species, i.e., different charges and masses. Each species can be separated and studied for transient variations. In addition, very sensitive measurements in BESS provide separation of isotopes of each particle, i.e., isotopes of hydrogen nucleus proton (p, $^1$H), deuterium (d, $^2$H), and tritium ($^3$H), antiproton ($\bar{p}$) as well as of helium nucleus ($^3$He, $^4$He). However, for this dissertation, isotopes of hydrogen nucleus are collectively used to study variations in proton intensities, which is the focus of my study.

I analyzed the data set that was available as DST (data storage and transfer) files which contain calibrated data, i.e., these have physical quantities, like rigidity, velocity, hit positions etc., derived from pulse height signals.

In the simplest form the analysis consists of the following steps:

(i) Use data from the DST files.

(ii) Select a specific species of particles (e.g. protons) using data selection cuts.

(iii) Calculate the flux of the selected particles that are incident at the top of the instrument (ToI). This flux is referred to as the ToI flux. During transit of the galactic
cosmic rays to the instrument there is an attenuation of primary particles and production of secondaries due to interactions in the Earth’s atmosphere. Therefore, the ToI flux contains mostly primary particles and some secondary particles.

(iv) Calculate the particle flux at the top of the atmosphere using the ToI flux. This requires the knowledge of atmospheric pressures and depths at which the instrument floats. In this context the term “atmospheric depth” or “atmospheric overburden” refers to the thickness of the residual atmosphere above the instrument and is measured in g cm$^{-2}$. The resultant flux is the absolute flux of primary particles incident upon the Earth’s atmosphere and is called the ToA flux. The ToA flux standardizes all particle fluxes whereas the ToI flux varies for different instruments and for different atmospheric overburden for the same instrument.

(v) Explore the flux for variations during whole flight, during individual days, or even smaller intervals.

(vi) Explore the flux for variations at a specific time interval but smaller energy intervals to see energy dependence of variations.

(vii) Explore the flux and spectrum for any features.

(viii) Ensure that the observed variations and features are real and not manifesting instrumental conditions.

These steps are discussed in detail below.

Figures 6.1(a) and 6.1(b) show a plot of dE/dx vs. rigidity and 1/\beta vs rigidity respectively for all positively charged particles from the DST files before any selection criteria have been applied.

6.1 Selection of particles

The data set primarily consists of particles of charges 1 and 2. These particles are electrons, positrons, muons, pions, and isotopes of hydrogen, isotopes of helium, and
the background. A particle is selected if it survives the preselection, fiducial cuts, quality cuts, and particle identification. These steps are described next.

### 6.1.1 Preselection

A “preselection” is carried out for all the particle species. This takes into account any instrument design limitations as well as any limitations caused due to certain flight conditions where any detector performed at less than its best efficiency. The following criteria are applied:

(a) Select single track events. A track where the number of hits inside JET is greater than 60% of $N_{\text{should}}$ is defined as a long track, where $N_{\text{should}}$ is the expected number of hits a calculated particle trajectory will make in the JET. In this dissertation nsd32, nsd40, and nsd48 refer to events that had at least 32, 40, and 48 hits in a track in the central region of the JET chamber. Unless otherwise specified, the figures in this dissertation pertain to nsd40.

(b) Only one or two hits in UTOF and LTOF are selected. When a particle passes close to an edge of the scintillator paddle, it may hit one or two adjacent paddles. The preselection requires only one hit in UTOF and one or two hits in LTOF. If $N_{\text{TOFU}}$ and
N_{TOFU} are the number of hits in UTOF and LTOF respectively, events with N_{TOFU} = 1 and N_{TOFL} = 1 or 2 are selected.

(c) Reject noisy hits in the JET. It is difficult to derive information for very noisy events. Hence, if N_{JET} is the number of hits inside JET, reject events where N_{JET} > 100 or number of segments > 15, where a segment consists of several consecutive hit points.

(d) TOF track matching in x. Check track residual in x (mm) for UTOF and LTOF. In the r-φ plane the extrapolated trajectory should pass through the UTOF and LTOF hit paddles. If X_{TRKU} and X_{TRKL} represent the x hit position from the center of the paddle in UTOF and LTOF respectively, |X_{TRKU}| < 75 mm and |X_{TRKL}| < 75 mm conditions ensure that the reconstructed track and the hit positions in the UTOF and LTOF indeed belong to the same particle event.

(e) Select 2-D reconstructed tracks. This means the tracks for which information on rigidity, β, and Chi-squared fit are not available should be discarded.

(f) Select only forward going particles. Reject albedo, i.e, the backward moving (β < 0) particles.

6.1.2 Fiducial cuts

The events within the fiducial volume of the instrument are selected as follows:

(a) Fiducial volume in x: If N_{center} is the expected number of hits in the central region of the JET chamber then N_{should} ≥ 32 and N_{center} > 0 defines the acceptable fiducial volume in the r-φ plane for the events. This eliminates the tracks that skim the outer most region of the tracking system where position measurement is less accurate than that in the central region due to distortion of the electric field in the chamber.

(b) Fiducial volume in z: the reconstructed trajectory in JET chamber is extrapolated to the hit positions in the UTOF and LTOF. Let the z hit positions, from the track, in the UTOF and LTOF be represented by Z_{TRKU} AND Z_{TRKL}. Then the cut,
( | $Z_{TRKU}$ | < 450 mm and | $Z_{TRKL}$ | < 450 mm), defines the fiducial region in the y-z plane and ensures that the particle actually passed through the scintillator paddles in the UTOF and LTOF detectors.

(c) **Hit pattern selection**: if the hit positions in UTOF and LTOF are in the paddles where both PMTs are bad in UTOF or one PMT is bad in LTOF or if both UTOF and LTOF are single-ended, the track is rejected.

(d) **Zenith angle cut**: for primary protons use the events such that the incident flux is nearly vertical, i.e., select events such that \( \cos(\theta_{\text{zenith}}) > 0.8 \). Here zenith angle, \( \theta_{\text{zenith}} \), is defined as the angle between the direction of incidence and zenith.

(e) the “Black-hole” cut: a region of JET chamber was not functioning well and hence, tracks passing through this region (defined as the “black hole”, or the BH, cut in this analysis) are rejected. For this region, \( y = 30 \) and the interpolated \( x \) is measured. These are used to calculate the signed distance \( S \) to the closest approach along the track. If a quantity \( z' \) is defined as \( z' = z \) track position + \( S \) dip angle, then the BH cut is defined as \((-160 < x < -80) \) and \((50 < z' < 150) \) [98].

The geometrical factor of the instrument is simulated to take account of these geometric selections.

### 6.1.3 Quality cuts

The quality cuts ensure that correct measurements have been made for incident energy. These are defined as follows.

(a) \( \chi_{r\phi}^2 < 5, \chi_{yz}^2 < 20 \), this reduced chi-square fit checks for quality of track fit.

(b) The track is extrapolated to estimate the hit position in the UTOF and LTOF. The estimated positions are required to match the actual hit positions in these detectors.

(c) **Hazard bit check**: each QDC board has an individual deadtime, during which a hazard bit is issued to the QDC. The hazard cut checks for the bad hit, hazard bit, or overflow conditions. This cut ensures that each QDC and TDC were working properly.
The events that survive the Preselection, Fiducial, and Quality cuts result in acceptable events for all particle species. This data set is then used for particle identification to distinguish between species.

6.1.4 Identification of protons

Particle identification is uniquely carried out by charge and mass as follows:

Particle selection by charge

Figure 6.2 shows the dE/dx selection band for p, d, and t for the UTOF detector. In this plot protons and deuteriums are clearly visible but only a hint of tritiums is present. It is clear from the plot that protons and deuteriums can be individually identified below rigidity \( \sim 2 \) GV but not for rigidity \( > 2 \) GV. In order to maintain consistency throughout the range of rigidities for this analysis the isotopes (p, d, and possibly t) are collectively used for particles of charge \( Z = 1 \) instead of just protons. The selection band lies between an upper edge and a lower edge. The dE/dx band selections are carried out independently for each detector. The particles selected by all detectors constitute data set of charge \( Z = 1 \) particles. For the analysis I selected particles by charge from UTOF, JET and LTOF.

Particle selection by mass

This selection is carried out independently of the selection by charge. In order to select particles by mass, \( 1/\beta \) band cut is used. The selection bands for protons and deuterium are shown in figure 6.3. Here, as in the dE/dx vs rigidity plots, it is clear that the isotopes of hydrogen cannot be separated beyond rigidity of \( \sim 2 \) GV. The particles that have been selected by mass are shown in figure 6.3.

Figure 6.4(a) shows \( 1/\beta \) vs rigidity for deuteriums for a specific data run. Deuterium contributed only \( \sim 0.6 \% \) to the total p+d selection. This shows that inclusion of
Figure 6.2: Particle selection by charge. The left column shows dE/dx vs. Rigidity for each detector; particles of charge Z = 1 are in regions enclosed by blue curves. The right column has same information for particles selected by the respective detector. The selection by each detector is made independently of other detectors.
Figure 6.3: Particles selection by mass (independent of selection by charge).

Figure 6.4: Deuteriums can be separated from protons at rigidities $< \sim 2$ GV but have been taken as a part of selection. Deuteriums make only $\sim 0.59\%$ of the selected [p+d] data set and this choice maintains consistency throughout observed energy range without significantly affecting the particle flux.
deuterium provides a consistent data set throughout the rigidity range without actually contributing significantly or adversely affecting the study of transient variations. Figure 6.4(b) shows that the background between p and d contributes \(\sim 0.15\%\) to the total p+d population. This is a small fraction and perhaps these are the particles that could not be clearly identified as p or d. This small fraction will not negatively impact the analysis.

After the \(dE/dx\) and \(1/\beta\) band cuts have been made, the particles that are selected by both of these cuts make the final sample of hydrogen isotopes.

![Graphs showing \(dE/dx\) vs. Rigidity and \(1/\beta\) vs. Rigidity](image1)

Figure 6.5: The final selected data set of [p+d].

There were 256 data runs of about 30 minutes each or longer. Particles selected from a data run are shown in figure 6.5. Particles were selected from each of these
data runs and then combined in order to provide a data set of selected particles for the BESS-Polar I flight. These particles were used to calculate flux in this analysis.

Efficiencies of selection cuts are shown next because they are used in flux calculations.

6.1.5 Efficiency of selection cuts

The efficiency of a specific selection criterion (cut) is calculated as follows:

\[
\text{the efficiency of a cut} = \frac{\text{Particles selected by this cut}}{\text{particles selected by all other criteria}}
\] (6.1.1)

Efficiencies of various selection cuts are shown in figure 6.6.

Figure 6.6: Efficiencies of selection cuts.

Determination of flux is explained next.

6.2 Determination of flux at the top of the instrument

Cosmic ray differential flux is defined as the number of particles per unit area per unit time per unit energy per unit solid angle. If \( N_{\text{obs}} \): number of observed protons, \( N_{\text{Top}} \): number of protons extrapolated to the top of instrument, \( \epsilon \): detection efficiency of
protons in the instrument, $T_{\text{live}}$: live time, and $S\Omega$: geometrical acceptance for protons then the differential ToI flux, $dF_{ToI}$, is given as:

$$dF_{ToI}dE = N_{\text{obs}}(E)\frac{1}{\epsilon S\Omega T_{\text{live}}}$$  \hspace{1cm} (6.2.1)

Estimation of efficiencies and exposure factor is explained next.

**The following quantities are calculated in order to determine the particle flux:**

$N_{\text{obs}}$, **the number of observed particles**

This is the number of particles that have been selected and identified as p+d as explained earlier in this chapter.

**6.2.1 Efficiency of particle detection ($\epsilon$)**

The efficiency of particle detection depends on the instrumental limitations, specific conditions during the flight, as well as the criteria used to select these particles. In general the efficiency of detection of particles is defined by

$$\epsilon = \frac{N_{\text{obs}}}{N_{\text{incident}}}$$  \hspace{1cm} (6.2.2)

The number of observed particles depends on the trigger, preselection, reconstruction of particle trajectory, and particle identification. Hence, the efficiency, $\epsilon$, can be rewritten as

$$\epsilon = \epsilon_{\text{Trigger}}.\epsilon_{\text{preselection}}.\epsilon_{\text{rec}}.\epsilon_{\text{PID}}\epsilon_{\text{acc}}$$  \hspace{1cm} (6.2.3)

where,

$\epsilon_{\text{Trigger}}$ is the trigger efficiency,

$\epsilon_{\text{preselection}}$ is the efficiency of preselection,
\( \epsilon_{rec} \) is the efficiency of track reconstruction,

\( \epsilon_{acc} \) is the efficiency of accidental hits being recorded as true events,

and \( \epsilon_{PID} \) is the efficiency of particle identification.

**Trigger efficiency (\( \epsilon_{Trigger} \))**

No sampling trigger was used for BESS-Polar I. The trigger efficiency is determined solely by the coincidence between the UTOF and LTOF or UTOF and MTOF detectors as well as the discrimination in the discriminator modules. The trigger efficiency is estimated to be \( \epsilon_{Trigger} > 99.0 \% \) [88].

**Efficiency of preselection (\( \epsilon_{preselection} \))**

This is the efficiency of incident particles passing through the fiducial volume of the detector and being recognized as single track events by each detector. This is estimated using the Monte Carlo simulation that includes the interaction processes and energy losses. This efficiency is given by

\[
\epsilon_{preselection} = \frac{N_{single}}{N_{Fiducial}}
\]  

(6.2.4)

where \( N_{single} \) and \( N_{fiducial} \) represent number of single track events and the number of particles passing through the fiducial volume respectively.

**Efficiency of track reconstruction (\( \epsilon_{rec} \))**

The tracking system has limitations very close to the sense wires in the JET chamber and the IDCs. This is due to the deadtime of FADC and may lead to failure in reconstruction of the particle trajectory, and hence may not result in a long track event even if enough hits were made in the tracking system. In order to estimate the track reconstruction efficiency, 1000 unbiased events with appropriate TOF hits and JET hits were scanned.
Out of these 1000 events, fewer than 10 showed failure to reconstruction of tracks. Hence, the estimated efficiency is given by $\epsilon = \epsilon_{rec} > 98.0 \pm 0.2\%$ [88].

**Efficiency of accidental hits (1 - $\epsilon_{acc}$)**

An accidental particle, which is not a true cosmic ray event, whose track can be reconstructed can pass through the scintillator counters and cause accidental hits. However, the BESS-Polar I Monte Carlo simulation did not simulate such events. Therefore, in order to calculate efficiency of such events, a random trigger was issued in the cycle of 10Hz during the whole flight. This trigger was independent of the particle passage. A scan of such random trigger samples led to an estimation of accidental hit events. This efficiency of rejection of accidental particles is found to be $> 97.0\%$.

**Efficiency of particle identification ($\epsilon_{PID}$)**

The efficiency of particle identification depends on the efficiencies of quality cuts ($\epsilon_Q$), $dE/dx$ band cut ($\epsilon_{dE/dx}$), $1/\beta$ band cut ($\epsilon_{beta}$), hazard bit cut ($\epsilon_{haz}$).

$$\epsilon_{PID} = \epsilon_Q \cdot \epsilon_{dE/dx} \cdot \epsilon_{beta} \cdot \epsilon_{haz}$$

(6.2.5)

**6.2.2 Exposure factor**

This factor is a combination of geometrical acceptance of the instrument and the time duration when the instrument was actively acquiring data, known as the live time.

$$Exposure\ factor = S\Omega . T_{live}$$

(6.2.6)

These quantities are determined as follows:

(a) Determination of the geometrical acceptance ($S\Omega$):

The geometry of the instrument defines the geometrical acceptance and its value
for the design of BESS-Polar detector is 3000 cm$^2$ sr (or 0.3 m$^2$ sr). However, the actual geometrical acceptance depends on the fraction of instrument volume that was operational during the flight. The geometrical acceptance is also a function of energy of the incident particles.

Determination of $S\Omega$ is carried out using the Monte Carlo simulation as follows:

(i) let a sphere of radius $R_A$ enclose the whole instrument.

(ii) the geometrical acceptance of this sphere for isotropic cosmic ray flux is $4\pi$(surface area of the sphere). However, for only downward flux, this becomes

$$S\Omega_A = \left(\frac{1}{2}\right) (4\pi)\pi R_A^2 = 2\pi^2 R_A^2$$  \hspace{1cm} (6.2.7)

(iii) particles are isotropically injected into the instrument with a solenoidal magnetic field of 0.8 T while keeping the energy loss and interaction switched off.

(iv) the preselection cuts from the particle selection process were applied in the simulation because these cuts take into account the actual effective fiducial volume during the flight. A quantity, $r_{fiducial}$, is obtained from

$$r_{fiducial} = \frac{\text{number of events that survived}}{\text{number of events that were generated}}$$  \hspace{1cm} (6.2.8)

(v) then the geometrical acceptance of the instrument is given by

$$S\Omega = S\Omega_A r_{fiducial}$$  \hspace{1cm} (6.2.9)

Figure 6.7 shows the geometrical acceptance of the BESS-Polar I instrument for $N_{\text{should}} = 40$. During this flight only 26 out of 44 TOF PMTs were operational\(^1\) The cutoff energy for the instrument due to the material in the path of the particles is $\sim 0.12$ GeV at the ToI for the upper and lower TOF and $\sim 0.1$ GeV for the upper and middle TOF

\(^1\)Chapter 5 described the work done to improve quality of the ToF subsystem for BESS-Polar II.
configuration. Below the cutoff energies, no sensitivity was assigned to the instrument during the simulation process [88].

(b) Determination of live time ($T_{live}$)

The instrument had 1 MHz clock pulse generator and scalers which directly measured the live time of the instrument. The total live time during the flight was 449936.9 seconds [88].

In addition to these quantities, ionization loss must be corrected for. Incident particles go through ionization loss in the layers of the detector.

### 6.2.3 Correction for ionization loss

As the incident cosmic ray particles traverse the layers of atmosphere and the upper layers of the detector before they are detected by the tracking system, they lose energy by ionization loss. If the ionization loss is $dE/dx$ in the material of thickness $x$, then
the energy of a particle after traveling the thickness \( x \) is given by

\[
E(x) - E(0) = \int_0^x \frac{dE}{dx} \, dx
\]  

(6.2.10)

where \( E(0) \) and \( E(x) \) represent the energy of the particle at depths 0 (ToI) and \( x \) respectively. It must be noted that the particles are not always vertically incident. Hence, the actual thickness of the material traversed depends on the vertical thickness of the matter and the zenith angle.

Calculated ToI flux for the whole flight is shown in figure 6.8.

![Figure 6.8: ToI proton flux for the whole BESS-Polar I flight.](image)

The next section describes the ToA flux.
6.3 Determination of flux at the top of the atmosphere

To obtain the flux at the ToA, the effects of overhead atmosphere must be corrected. The observed flux is a combination of primary flux and the secondary flux \[105], \[78].

\[
dF_{ToI}dE = dF_{primary}^{ToI}dE + dF_{secondary}^{ToI}dE
\] (6.3.1)

where, \(dF_{primary}^{ToI}dE = \eta dF_{ToA}dE\) with \(\eta\) being the survival probability of primary protons in the atmosphere. The secondary protons are given using a yield function \(Y(E, E')\) which provides the number of secondary protons in energy range \(E\) and \(E+dE\) that were created as a result of interaction of primaries of energy \(E'\). This gives \(dF_{secondary}^{ToI}dE = (\int_{E}^{\infty} Y(E,E')dF_{ToA}^{secondary}(E')dE')\) dE and

\[
\Rightarrow dF_{ToI}dE = \eta dF_{ToA}dE + \int_{E}^{\infty} Y(E, E')F_{ToA}(E')dE'
\] (6.3.2)

where, \(dF_{ToA}\) represents the ToA flux. The secondary flux can be written as \(dF_{secondary}^{ToI}dE = R_{air}dF_{ToA}dE\) with \(R_{air}\) as the fraction of secondary (to primary) protons produced in the atmosphere. Hence, 6.3.1 can be rewritten as

\[
dF_{ToI}dE = \eta dF_{ToA}dE + R_{air}dF_{ToA}dE
\] (6.3.3)

\[
\Rightarrow dF_{ToA}dE = \frac{dF_{ToI}dE}{(\eta + R_{air})}
\] (6.3.4)

If \(N_{obs}\) is the number of observed protons, \(N_{ToA}\) is the number of protons at the top of atmosphere, and \(N_{atmosph}\) is the number of secondaries generated in the Earth’s atmosphere then these quantities are related as:

\[
N_{ToA} = \frac{(N_{ToI} - N_{atmospheric})}{(\eta + R_{air})}
\] (6.3.5)
Then the differential flux \( (dF_{T_oA}) \) of a species of particles (proton) at the top of atmosphere integrated in energy interval \( dE \) is given by

\[
dF_{T_oA}dE = N_{obs} \cdot \frac{1}{c} \cdot \frac{1}{S\Omega T_{live}} \cdot \frac{1}{\eta(E) + R_{air}(E)}
\]  \hspace{1cm} (6.3.6)

The survival probability is calculated using the atmospheric overburden, \( (d_{air}) \) and the zenith angle of the particles; the thickness a particle actually traverses is given by \( d_{air}/\cos(\theta_{zenith}) \). The atmospheric secondary particles correction was calculated using the method developed by [61] and [69].

The next section is a brief overview of atmospheric corrections needed to propagate the ToI flux to ToA flux.

### 6.3.1 Need for sensitive atmospheric corrections

The secondary proton flux depends on the thickness of the atmosphere above the detector. Greater thickness results in more secondary particles at lower energies as well as a greater loss of the lowest energy primary particles in the atmosphere. This effect is more pronounced especially for particles of energies \(< 200 \text{ MeV} \). Space based experiments do not face this problem. However, balloon-borne detectors float at varying altitudes, ranging from \( \sim 3-6 \text{ g cm}^{-2} \), thus requiring a sensitive correction for effects of Earth’s atmosphere on the primary cosmic ray flux. Figure 6.9 shows the atmospheric overburden during the BESS-Polar I flight. The thickness of atmosphere continuously changed between \( \sim 3.8 \text{ g cm}^{-2} \) and \( \sim 5.4 \text{ g cm}^{-2} \). Calculation of overall whole flight ToA flux used 4.33 g cm\(^{-2}\) atmospheric overburden but it is obvious that this will not provide a very accurate estimation of secondary proton flux. The estimation of daily flux of secondary protons used the average daily atmospheric depths. ToI fluxes for time intervals of 4-hour were calculated using the 4-hour averages of atmospheric overburden and provide more accurate estimates.
Figure 6.9: BESS-Polar I overburden of the Earth’s atmosphere (gray), daily averages (red), 4-hour averages (blue), whole flight average (green).

6.3.2 Concept of Atmospheric corrections

In order to calculate ToA flux from the ToI flux, all possible mechanisms of interaction in the atmosphere must be considered.

Loss of primary particles

At low energies the primaries are lost and spectrum is modified due to ionization losses. Loss of particles also occurs at all energies due to the interaction of cosmic rays with the atmospheric particles. Protons are also gained or lost due to charge exchange in high energy interactions. There is a probability, $\alpha = 0.333$, that a cosmic ray proton can undergo charge exchange and become a secondary neutron [61]. At relativistic energies the atmospheric corrections for protons are very small and primary protons lose energy in inelastic nucleon interactions or spallation of heavier nuclei in Earth’s atmosphere.
Production of secondary particles

At non relativistic energies, in addition to the energy loss mentioned above, secondary protons are produced when incident cosmic ray interacts with nuclei in the atmosphere, viz., in the interactions involving recoil of target nucleons and evaporation of target nuclei. In recoil process a nucleon in the target nucleus may collide directly with the interacting nucleon or a secondary particle resulting in recoil nucleons coming out of target nucleus; the distribution of secondaries is maximum in forward direction. Evaporation of a target takes place when an incoming cosmic ray particle transfers enough energy to the nucleus causing it to become unstable and then evaporate into fragments. Angular distribution of these secondaries is nearly isotropic. Spallation produces secondary protons in interaction of helium or heavier nuclei in the Earth’s atmosphere. In high energy interactions a proton can lose energy without considerably altering its direction and result as a secondary at lower energies. Hence effects of atmospheric overburden, energy dependence, and angular distribution must be taken in to account.

Papini et al. provided fit functions for contribution to secondary particles for the above processes for solar minimum and maximum fluxes [61].

Figures 6.10(a) and 6.10(b) show the ToI, ToA and secondary flux and the ratio of ToI and ToA respectively for a typical 4-hour time frame. At lowest energies the flux is dominated by secondary protons and at at high energies the secondary flux decreases. At energies above 1.0 GeV the flux is mainly primary.

Some contributors of error are explained next.

6.3.3 Contributors of Errors

Several factors contribute to the overall error in calculation of flux. These factors of statistical and systematic errors can be seen from eq. 6.3.6, which shows the errors can
be expressed as

\[ \frac{\Delta F_{TOA}}{F_{TOA}}^2 = \left( \frac{\Delta N_{obs}}{N_{obs}} \right)^2 + \left( \frac{\Delta \epsilon}{\epsilon} \right)^2 + \left( \frac{\Delta (S \Omega)}{(S \Omega)} \right)^2 + \left( \frac{\Delta T_{live}}{T_{live}} \right)^2 + \left( \frac{\Delta (\eta(E) + R_{air}(E))}{(\eta(E) + R_{air}(E))} \right)^2 \] (6.3.7)

These terms are discussed next.

### 6.3.4 Statistical error

The first term of equation 6.3.7 is the statistical error. The confidence level of 68.27% corresponds to 1\(\sigma\) for a Gaussian distribution. As referenced in Matsuda’s PhD dissertation [88], this was achieved by adapting Feldman’s “unified approach” [45] and Nayman’s “confidence belts method” [93]. The statistical errors were calculated using the inverse chi-square distribution under the assumption that the number of observed events has a Poisson distribution [78].

If true Probability distribution for obtaining \(n\) events in an experiment can be expressed by a Poisson distribution. If \(\mu\) is the true mean number of counts and \(B\) is the
background then the Poisson distribution is given by

\[ P_\mu(n) = e^{-(\mu + B)} \frac{(\mu + B)^n}{n!} \]  

(6.3.8)

If \( \mu_1 \) and \( \mu_2 \) denote the minimum and maximum values of a confidence interval, corresponding to events \( n_1 \) and \( n_2 \) respectively, then the following condition is satisfied:

\[ \sum_{n_1}^{n_2} P_\mu(\nu)(n) \leq 68.27\% \]  

(6.3.9)

6.3.5 Systematic errors

The remaining terms in eq. 6.3.7 contribute to the systematic error.

Background subtraction

For primary protons, the background comes from light particles; these are muons, pions, and positrons. These can be clearly separated from the protons below 1.0 GeV (rigidity \( \sim 1.7 \) GV) but above that the protons cannot be separated from these light particles. The albedo negatively charged particles can also contribute to the background but the upward moving particles are clearly separated and were not included in this analysis so their contribution was neglected.

Efficiency of particle selection

The selection efficiency is made up of the trigger efficiency, efficiency of track reconstruction, efficiency of selecting a single track, and efficiency of particle identification. Errors in these efficiencies were reduced by use of low energy protons and antiprotons during a beam test of the detector. Such errors mainly occur due to interaction losses in the instrument and were estimated by Monte Carlo (GEISHA) simulations. The systematic
error was estimated to be ([88]):

$$\left( \frac{\Delta \epsilon}{\epsilon} \right) = \begin{cases} 
\pm 5\% & (E_{ToI} < 0.3 \text{ GeV}). \\
\pm 2\% & (0.3 \text{ GeV} < E_{ToI} < 1.0 \text{ GeV}). \\
\pm 5\% & (1.0 \text{ GeV} < E_{ToI}). 
\end{cases} \quad (6.3.10)$$

**Live time**

The resolution for measurement of live time was $10^{-6}$ seconds and the fraction of dead
time was $\sim 15\%$. Thus the error in live time could be considered negligible [88].

**Geometrical acceptance**

Monte Carlo, simulation was used to calculate the geometrical acceptance of BESS-Polar detector by turning off all interactions and energy loss mechanisms. The fiducial volume cuts were applied during this simulation. The main source of this error is the uncertainty in the alignment of the detector. This systematic error was estimated to be $< 1\%$ [88].

**Survival of primary and production of secondary protons**

The uncertainty in the interaction cross section contributes to the uncertainty in loss of primary protons by interactions and residual atmosphere above the detector. For an event trigger by the UTOF and LTOF, the residual air of $\sim 4.4 \text{ g/cm}^2$ corresponds to $1/2$ the detector material. This error was estimated to be $\sim 1\%$.

**Error in estimation of energy**

An error in reproduction of a straight track for particles of infinite energy contributes to error in estimation of energy. This can appear as a shift in the $1/R$ scale. $\Delta 1/R = 0.0042$ was taken, corresponding to the maximum detectable rigidity and related to the
accuracy of calibration of tracker for very high energies ($1/R = 0$). Error in uniformity of the magnetic field and its strength can contribute to an error in energy measurement. This was taken to be $\Delta E/E = 0.005$ [88].

The overall statistical and systematic errors for whole flight are shown in figure 6.11.

![Statistical and systematic errors](image)

Figure 6.11: Statistical and systematic errors.

Once the proton fluxes are calculated for the whole flight, daily, and 4-hour time intervals, they are analyzed for short-term variations. This is discussed next.

### 6.4 Exploring the daily particle flux for variation

Comparison of daily protons fluxes (an example in figure 6.13) showed variations. These variations are small and hence, in order to produce a more detailed picture of observed variations, the whole flight flux (figure 6.12) was used to normalize each daily flux. Henceforth, unless otherwise specified, the term “normalized flux” refers to a flux normalized by the whole flight flux.

If the changes in flux are caused due to the instrument, the same effect should be incorporated in the flux every day if this instrument restriction persisted throughout the flight. Normalization of daily flux by the average flight flux should neutralize such
Figure 6.12: Proton flux for the whole flight (used to normalize the daily fluxes).

Figure 6.13: Proton flux for December 13 and December 21.
instrumental effects. It is also possible that some part of the instrument does not function efficiently during parts of flight. These conditions affect detection efficiency, and hence overall flux. Any such known issues have been taken into account while calibrating the data and do not appear to affect the observations. The calibration is carried out at much finer time scales (∼ 0.5 hr) than the smallest time intervals used to study variations (∼ 4 hrs) and hence, observed variations are not instrumental effects. Figure 6.14 shows the daily normalized fluxes. Each curve represents one daily flux.

Figure 6.15 explores these variations in some more detail. Each panel has normalized flux for two consecutive days. There is clear variation in flux from day to day. Out of these the biggest change between two consecutive days occurred between December 15 and 16 with a maximum increase of ∼ 5 % around 0.4 GeV.
Figure 6.14: The normalized ToI and ToA fluxes have overall similar structures because ToA flux was calculated using the ToI flux.
Figure 6.15: Daily fluxes normalized to the whole flight flux.
Observations of variations of daily fluxes (figure 6.15) are summarized in table 6.1. The whole energy range is divided into three intervals for a closer look. As expected, the

<table>
<thead>
<tr>
<th>Day in Dec.</th>
<th>Flux behavior for Energy 0.1-1.0 GeV</th>
<th>Flux behavior for Energy 1.0-10.0 GeV</th>
<th>Flux behavior for Energy 10.0-100.0 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>13 - 14</td>
<td>1. decreases below $\sim$ 300 MeV. 1. increases up to 1.3 GeV. 2. Crosses around 1.3 GeV but somewhat decreases. 1. no clear pattern for change can be specified.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2. increases from $\sim$ 300 MeV to 1.0 GeV.</td>
<td>2. up to 1.3 GeV increase is greater $\sim$ 5% and above, the increase is smaller, $\sim$ 2 %.</td>
<td></td>
</tr>
<tr>
<td>15 - 16</td>
<td>1. decreases below 0.2 GeV.</td>
<td>1. increases.</td>
<td>1. clear increase up to 30 GeV.</td>
</tr>
<tr>
<td>16 - 17</td>
<td>1. decreases up to $\sim$ 300 MeV. 2. crosses around 300 MeV and starts increase.</td>
<td>1. overall increase.</td>
<td>1. Not clear change.</td>
</tr>
<tr>
<td>17 - 18</td>
<td>1. increases up to $\sim$ 300 MeV. 2. appears to cross but not clear.</td>
<td>1. increases.</td>
<td>1. increases up to $\sim$ 30 GeV</td>
</tr>
<tr>
<td>18 - 19</td>
<td>1. increases.</td>
<td>1. increases up to 7 GeV not clear above that.</td>
<td>1. not clear.</td>
</tr>
<tr>
<td>19 - 20</td>
<td>1. increases. 2. greater increase up to $\sim$ 300 MeV. Slower above.</td>
<td>1. increases.</td>
<td>1. not clear.</td>
</tr>
<tr>
<td>20 - 21</td>
<td>1. decreases consistently.</td>
<td>1. decreases.</td>
<td>1. decreases till 20 GeV. not clear above that.</td>
</tr>
</tbody>
</table>

Table 6.1: Summary of observed daily variation of BESS-Polar I proton flux

daily fluxes do not seem to vary much above 10 GeV because particles with such high energies do not get modulated in the heliosphere. Due to lower statistics above 10.0 GeV, there is no clear picture of variation in that energy range. The intensities appear to be stabilizing towards the end of the flight because from 19th to 21st of December, the changes in flux are consistent in all energy ranges and are gradual. A few of these normalized spectra show that when flux at higher energies decreases, the flux at lower
energies increases. This could be explained by the fact that some particles from higher energies shift towards lower energies as a result of energy losses.

The next section explores for variations in shorter time intervals of 4 hours.

6.5 Variation analysis for 4-hour time windows

In order to carry out a more in-depth analysis of the observed variations, the data set from the whole flight was divided into windows of 4 hours. The ToI flux was calculated individually for each 4-hour window. Atmospheric depth for each 4-hour window was used to apply atmospheric corrections to the ToI flux, which were then used to calculate the ToA flux. As shown in figure 6.9, the 4-hour analysis provides more accurate atmospheric corrections because the average atmospheric overburden for each 4-hour time slot is closer to the actual depth.

The original binning used was 45 bins for 0.1 - 100.0 GeV range, with equal bin widths and 15 bins/decade of energy in log scale. The flux for each 4-hour window was rebinned for wider energy ranges to provide better statistics in each energy bin. Here I discuss analysis of fluxes divided into three and seven energy intervals.

6.5.1 4-hour fluxes with 3 wide energy intervals

Proton flux in the range 0.1 - 100 GeV for each 4-hour time interval was divided into 3 energy intervals, 0.1 - 1.0 GeV, 1.0 - 10.0 GeV, and 10.0 - 100.0 GeV. The whole flight ToA flux, was also divided into the same energy interval for normalization. The original energy ranges used for differential flux and the wider energy ranges with the integral flux are shown in figure 6.16. Time progression of normalized flux for each of these 3 energy ranges are summarized next.
Particles with energies 0.1 - 1.0 GeV

Each point in figure 6.17(a) represents normalized flux of particles between 0.1 - 1.0 GeV for a 4-hour time window during BESS-Polar I flight. There was an overall increase in the flux through the flight with an overall maximum variation of $\sim 11\%$. The slope of increase is sharper between Dec. 13 and 16, there is a sharp increase on December 16, the rate of increase slows down after December 16 and mostly remains flat with small increase or decrease from one 4-hour window to next. This pattern continues till December 19. After that there is slightly increasing flux and a daily periodicity appears.
(a) 4-hour proton flux (0.1 - 1.0 GeV), max variation $\sim 12\%$.

(b) 4-hour proton flux (1.0 - 10.0 GeV), max variation $\sim 10\%$.

(c) 4-hour proton flux (10.0 - 100.0 GeV), max variation $\sim 4\%$.

Figure 6.17: 4-hour normalized proton fluxes.
Particles with energies 1.0 - 10.0 GeV

Figure 6.17(b) shows an overall increase in the flux throughout the flight with an over all maximum variation of $\sim 10\%$. The slope of increase is sharp ($\sim 2\%/\text{day}$) from December 13-17, slows down after December 17, following which a gradual increase continues till December 21. After December 17 the normalized flux has a maximum and a minimum each day, somewhat like a periodic variation.

Particles with energies 10.0 - 100.0 GeV

There was an overall increase throughout the flight (figure 6.17(c)) with a maximum variation of $\sim 4\%$, the slope of this time progression changes around December 17 but the overall variation is much smaller than the two lower energy ranges. The rate of increase slows down after December 17. This gradual increase continues till December 18, after which the flux starts to stabilize. These highest energy particle flux intensities show variations although smaller compared with those at lower energies. But an interesting aspect is that however small, they do show variations. There is a “dip” between December 17 and 18. I checked the conditions of PMTs and while there are some sudden changes during flight, they do not coincide with this time frame.

Is the observed transient variation real?

The main questions that must be answered include, is the variation a contribution of instrumental conditions? is the variation caused due to instrumental response being different at different energies? was instrument functioning differently on different days? This variation is observed in ToI as well as the ToA fluxes. The variation and its features seem to be energy dependent. The highest energy flux (10.0 - 100.0 GeV) undergoes relatively less variations, and hence this flux can be used to normalize the flux for the two lower bins to further neutralize any potential effects of instrumental behavior or
similar contributions to observed variations. Figure 6.18 compares how flux variations in one energy range progress with respect to that in other energy ranges. Except for a consistent increase in the flux, the variation is not symmetric in all energy ranges. The slope of this variation differs, especially with respect to the highest energy particles observed. The slope, while having a subtle change, is more or less uniform for the ratio of fluxes in the two lower energy regions. This agrees with the understanding that lowest energy particles are more highly modulated and hence these two ranges (0.1 - 1.0 GeV and 1.0 - 10.0 GeV) show similar variations and the degree of variation is slightly smaller in 1.0 - 10.0 GeV range. It is interesting to note that while the 1.0 - 10.0 GeV flux exhibits oscillating behavior, its ratio with the flux of 10.0 - 100.0 GeV does not (figure 6.18(b)). This indicates that although such oscillating behavior cannot be clearly seen in the 10.0-100.0 GeV flux due to low statistics, it must be present to cancel the effects in the ratio.

4-hour fluxes in smaller energy intervals are discussed next.

6.5.2 4-hour fluxes with 7 wide energy intervals

To explore energy dependence of observed variations in more detail, I combined the differential flux into 7 energy intervals (figure 6.19) of different widths instead of using equal widths as in previous 3-bin analysis. These energy intervals were selected to get similar and excellent statistics (~ 0.3 % statistical error) in each interval. In order to select the wider energy ranges, I used the number of particles in the whole flight. The table 6.2 lists these wider energy ranges. An example of fluxes for these energy ranges is shown in figure 6.20. The time progression of normalized fluxes for all 7 energy intervals are shown in figures 6.21, 6.22, 6.23, 6.24, 6.25, 6.26, and 6.27.

Behavior of fluxes for these energy ranges is summarized in table 6.3.
(a) Ratio of normalized (0.1 - 1.0 GeV) and (10.0 - 100.0 GeV) fluxes.

(b) Ratio of normalized (1.0 - 10.0 GeV) and (10.0 - 100.0 GeV) fluxes.

(c) Ratio of normalized (0.1 - 1.0 GeV) and (1.0 - 10.0 GeV) fluxes.

Figure 6.18: Ratio of normalized flux of various energy intervals.
<table>
<thead>
<tr>
<th>Bin number</th>
<th>Energy range (GeV)</th>
<th>Number of particles</th>
<th>Approximate number for 4-hour</th>
<th>$\sqrt{N}$ for 4-hour</th>
<th>% error for 4-hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1 - 0.46</td>
<td>4657993</td>
<td>93159</td>
<td>305.22</td>
<td>0.33</td>
</tr>
<tr>
<td>2</td>
<td>0.46 - 0.86</td>
<td>5528797</td>
<td>110575</td>
<td>323.53</td>
<td>0.30</td>
</tr>
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Table 6.2: Details of energy range rebinning using proton flux for the whole flight.

Figure 6.19: Whole flight flux with original (Black) and wider energy intervals (Blue). The bars represent widths of new energy bins.
Figure 6.20: 4-hour proton flux (1.36 - 2.15 GeV)

Figure 6.21: Normalized 4-hour proton flux (0.1 - 0.46 GeV)
Figure 6.22: Normalized 4-hour proton flux (0.46 - 0.86 GeV)

Figure 6.23: Normalized 4-hour proton flux (0.86 - 1.36 GeV)
Figure 6.24: Normalized 4-hour proton flux (1.36 - 2.15 GeV)

Figure 6.25: Normalized 4-hour proton flux (2.15 - 3.41 GeV)
Figure 6.26: Normalized 4-hour proton flux (3.41 - 6.31 GeV)

Figure 6.27: Normalized 4-hour proton flux (6.31 - 100.0 GeV)
<table>
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<th>Energy range [GeV]</th>
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<th>Features?</th>
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| 0.1 - 0.46        | 1. overall increase.  
                    2. rate of increase slows  
                    3. although slope changes on 17, can be fit with one straight line.  
                    2. The periodic behavior seems to start between Dec 16-17 but some transition takes place between Dec 17-19. |
| 0.46 - 0.86       | 1. overall increase.  
                    2. slope change on 16 - 17.  
                    3. ~ 13.0% maximum variation. | 1. A small peak between Dec 17-18, which marks start of stabilized, periodic behavior but some process affects this pattern and changes the shape of amplitude of this periodicity. |
| 0.86 - 1.36       | 1. overall increase.  
                    2. slope change on 16 - 17.  
                    3. ~ 12.4% maximum variation. | 1. Periodic behavior after Dec 17.  
                    2. the small peak of the previous energy interval seems to be reducing in amplitude.  
                    3. Some process clearly affects the periodic behavior, which by comparison with the following days may have continued with a daily maximum and a minimum. |
| 1.36 - 2.15       | 1. overall increase.  
                    2. slope change on 16-17.  
                    3. ~ 12.4% maximum variation. | 1. well defined periodic peaks and dips, after Dec 17.  
                    2. beginning of a small dip between 17-18 where a peaked used to be for lower energies. |
| 2.15 - 3.41       | 1. overall increase.  
                    2. slope change on 16-17.  
                    3. ~ 10.6% maximum variation. | 1. Periodic flux with peaks and dips after Dec 17.  
                    2. a large dip around Dec 17, 17-18 where a clear periodicity starts. These particles seem to have been more affected by some disturbance. |
| 3.41 - 6.31       | 1. overall increase.  
                    2. slope change around 16-17.  
                    3. ~ 8.4% maximum variation. | 1. Periodic flux with daily maximum and minimum.  
                    2. amplitude of the dip around Dec 17 has increased.  
                    3. These particles seem to have been more affected by some disturbance around Dec 17. |
| 6.31 - 100.0      | 1. overall increase although smaller than lower energies.  
                    2. slope change around 16-17.  
                    3. ~ 4.6% maximum variation. | 1. Periodic flux with daily maximum and minimum.  
                    2. higher amplitude of the dip  
                    3. A clear periodic flux may have started around Dec 16 but was distorted around Dec 17 due to some physical process. |

Table 6.3: Details of observed variations in 4-hour normalized fluxes.
Most of these fluxes show fast increase till December 17 followed by a gradual increase and stabilizing flux. Fluxes for all energy intervals show some changing behavior between Dec 17 and 18, this indicates that some physical process occurred between the times the flux was recovering at the beginning and when it was stabilizing with a periodicity. This was a transition region for the fluxes and is seen as a distortion of lower energy flux pattern and a clearly visible decrease, or a “dip”, for energies above \(\sim 1.0 \text{ GeV}\). This effect becomes more pronounced for energies above 2.0 or 3.0 GeV. Just like the 3-bin analysis, this shows that BESS-Polar I was on the recovery phase of a cosmic ray decrease.

The periodic behavior seems to be present much before December 17 and seems clearer at energies above 0.86 GeV but the pattern is more distorted due to the possible effects of processes that caused the decrease shortly before BESS was launched. It is easier to separate the structures and study the causes when several processes are not involved. Therefore, I have focused on the periodic behavior exhibited after December 17.

There is a peak between December 17 and 18 for energy ranges 0.1 - 0.46, 0.46 - 0.86, and 0.86 - 1.36 GeV. The amplitude of this peak decreases with increase in energy. A “dip”, whose amplitude increases with increasing energy is observed at the same location for higher energy ranges, viz., 1.36 - 2.15, 2.15 - 3.41, 3.41 - 6.31, and 6.31 - 100.0 GeV.

So we see three main “features” in our 4-hour proton fluxes; an increasing flux at the beginning of the flight (Feature I), somewhat of a “transition region” characterized by a peak at lower energies and a dip at higher energies around December 17 (Feature II), this is followed by a stabilizing quasi-periodic flux towards the end of the flight (Feature III).

Next section explores these features for energy dependence.
6.6 Energy dependence of observed features

This section explores the energy dependence of observed features in the BESS-Polar I proton flux. The slope of rising flux for Feature I, the amplitude of the dip (or peak for energies $< 1.0$ GeV) for Feature II, and the amplitude of the periodic flux for Feature III have been used to see their dependence on energy (figure 6.28).

Using a very basic comparison the energy dependence of these features can be summarized as follows:

Feature I: slope has an overall decreasing trend. So higher energy particles recover slower as compared to the lower energy particles.

Feature II: the “transition region”: No specific peak or dip structure could be identified for the lowest energy intervals. For energies above that, there is a small peak for two intervals; the amplitude of the peak decreases with increasing energy. At the same spot there is a dip for higher energies; its amplitude increases with increasing energy. So higher energy particles are lost (more) in this dip.

Feature III: Amplitude of periodic variation decreases. It appears that even with this diurnal like variations, the flux is still recovering/rising. This last part may be true for the higher energy particles as well but the rise is slower so they appear to either not be rising or rising very slowly.

Proton fluxes are presented next.

6.7 Flux data from BESS-Polar I flight

The time progression of the proton flux ($[\text{m}^{-2} \text{ s}^{-1} \text{sr}^{-1} \text{GeV}^{-1}]$ from BESS-Polar I is presented in this section. The data are in averages of 4 hours. If you would like flux data for other energy or time intervals, please contact me at Neeharika.Thakur@gmail.com.
(a) Feature I dependence: Slope of recovery.

(b) Feature II dependence: amplitude of the dip.

(c) Feature III dependence: amplitude of the periodic behavior.

Figure 6.28: Energy dependence of the three observed features. Horizontal bars represent energy interval for a given point.
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Table 6.4: Time progression of (0.1 - 0.46 and 0.46 - 0.86 GeV) ToA p flux.
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Table 6.5: Time progression of (0.86 - 1.36 and 1.36 - 2.15 GeV) ToA p flux.
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Table 6.6: Time progression of (2.15 - 3.41 and 3.41 - 6.31 GeV) ToA p flux.
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Table 6.7: Time progression of (6.31 -100.0 GeV) ToA p flux.
6.8 Summary

Proton fluxes for the whole flight, each day and for each 4-hours were calculated using BESS-Polar I data. Daily fluxes show variations in flux intensities mainly in energy range 0.1 - 10.0 GeV. Some variations are seen even at $\sim 30$ GeV. A more detailed analysis at 4-hour time intervals allowed for sensitive atmospheric corrections, which are especially important at the lowest energies where the most variations are seen. Dependence of variations on energies was explored by studying the flux at different energy intervals. For 4-hour fluxes variations up to $\sim 10 - 14\%$ were seen in the lowest energy ranges. While usually variations are not observed at energies beyond 10 GeV, the fluxes at the highest energy range also show variations. In the case of the 7 energy ranges presented here variations seen for the highest energy, bin 7, can be explained by the fact that the highest energy range is wide and is dominated by the lower energy particles. However, the 3-bin analysis also shows some variations in the energy range 10 - 100 GeV so we can say that variations observed at higher energies are real.

Here I have used the 4-hour normalized fluxes to summarize the observed features.

The three main features observed in the time progression of proton fluxes are:

(i) Feature I: an overall rise in flux for the first few days at the beginning of the flight. BESS flight occurred at the recovery phase of some decrease. This is true for different energy ranges in the 4-hour intervals as seen in figure 6.28(a). For the lowest energy ranges (0.1 - 0.46 GeV and 0.46 - 0.86 GeV) the flux increases ($\sim 8-9\%$) until December 16 followed by a sharp decrease in flux between December 16-17 and then the flux rises again. For all other energy ranges, the flux continues to rise till December 17 and this increase is smallest ($\sim 3\%$) for the highest energy range (6.31 - 100.0 GeV).

(ii) Feature II: a “transition region” between December 17 and 18. A dip is present at energies above $\sim 1.0$ GeV and its amplitude increases with increase in energy. For the highest energy range (6.31 - 100 GeV), this dip is $\sim 3\%$ after which the flux rises
by $\sim 4\%$ within the same day. At the corresponding time the flux at energies below 0.46 GeV shows a distortion in a pattern which could have been a periodic behavior. At energies above 0.46 GeV, there is a peak at this point, which could have been a peak of the periodic behavior. For the energies between 0.46 - 1.36 GeV, where the periodic behavior is apparent, the peaks decrease in amplitude at this time. So the size of the “dip” increases for higher energies and for lower energies, if there is a peak, its amplitude decreases.

The dip is present in time progression of fluxes for wider energy ranges as well. For 1.0 - 10.0 GeV, the dip has $\sim 2\%$ decrease and $3\%$ rise whereas for energy range 10.0 - 100.0 GeV the dip has $\sim 3\%$ decrease and $3\%$ rise.

(iii) Feature III: start of stabilizing flux after December 17 - 18 with a daily maximum and a minimum. This periodic flux has an amplitude and a phase. At lower energies this periodic behavior is more erratic and has higher amplitudes than those in the higher energy particles. The lowest energy particles must have been more affected by the disturbance and may have taken longer to stabilize. It is possible that they would have shown a similar behavior after a longer time had passed, for them to stabilize and exhibit a well defined periodic pattern, after BESS-Polar I flight was successfully terminated. This oscillating behavior appears to be somewhat like diurnal variations. I refer to this behavior as "quasiperiodic flux".

The next chapter attempts to correlate these variations and features to physical characteristics of the heliosphere during the BESS-Polar I flight.
Chapter 7

Physical Interpretation

In an attempt to understand the variations and features observed in the time progression of BESS proton energy spectrum as seen in Chapter 6, careful comparisons with data from a few other experiments have been made. Comparative experiments are used to confirm the findings of BESS whereas the complementary experiments are used to correlate the variations with physical conditions in the local heliosphere. Hams et al. [66] and Orito et al. [62] presented an initial analysis and outlook for short-term variations in BESS proton fluxes.

This chapter starts with a list of experiments and their measurements that have been used for comparison with BESS-Polar I proton flux. Then a brief summary of reported general solar activity and geomagnetic activity during the BESS-Polar I flight is presented. Time variation of BESS proton flux is compared with data from the neutron monitors. This is followed by a comparison with solar wind plasma and IMF data in order to interpret the physics of the features observed in BESS data.

The compared experiments are listed in the next section.
7.1 Compared Experiments and measurements

Data from several neutron monitors were used for a comparative exploration of our findings. Complementary measurements of IMF and solar wind plasma and particles were compared.

7.1.1 Neutron monitors

The geomagnetic field can be used as a spectrometer for cosmic rays. The magnetic latitude of a neutron monitor determines the lowest magnetic rigidity of a primary particle that can reach the detector. The amount of overlaying atmosphere depends on the detector’s altitude so a neutron monitor at higher altitude will typically have higher count rates compared with a similar neutron monitor at a lower altitude [3]. Figure 7.1 shows a few neutron monitors around the world. The neutron monitor data were taken from Bartol neutron monitor website [3], Space Physics Interactive Data Resources (SPIDR) [7] and some neutron monitor station information were supplemented from Izmiran network of cosmic ray stations [95]. Table 7.1 lists a few of the 41 neutron monitors whose data were studied. The next section lists experiments used for solar wind plasma data.

![Neutron monitors around the world](image)

Figure 7.1: Neutron monitors around the world [5].
### Neutron Monitor Locations

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>McMurdo (near the geomagnetic south pole)</td>
<td>166.6</td>
<td>-77.9</td>
<td>48</td>
<td>0.01</td>
</tr>
<tr>
<td>South pole (world’s most sensitive for relativistic CRs)</td>
<td>0.0</td>
<td>-90.0</td>
<td>2820</td>
<td>0.09</td>
</tr>
<tr>
<td>Inuvik</td>
<td>-133.7</td>
<td>68.4</td>
<td>21</td>
<td>0.17</td>
</tr>
<tr>
<td>Fort smith</td>
<td>111.93</td>
<td>60.02</td>
<td>206</td>
<td></td>
</tr>
<tr>
<td>Thule</td>
<td>-68.7</td>
<td>76.5</td>
<td>26</td>
<td>0.0</td>
</tr>
<tr>
<td>Newark</td>
<td>-75.7</td>
<td>39.7</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Mawson</td>
<td>62.88</td>
<td>-67.6</td>
<td>0</td>
<td>0.22</td>
</tr>
<tr>
<td>Sanae</td>
<td>-2.85</td>
<td>-71.67</td>
<td>53</td>
<td>1.06</td>
</tr>
<tr>
<td>Santiago</td>
<td>-70.71</td>
<td>-33.48</td>
<td>512</td>
<td>11.44</td>
</tr>
<tr>
<td>Climax</td>
<td>-106.18</td>
<td>39.37</td>
<td>3400</td>
<td>3.03</td>
</tr>
<tr>
<td>Mexico city</td>
<td>-99.2</td>
<td>19.33</td>
<td>2274</td>
<td>9.53</td>
</tr>
<tr>
<td>Tibet</td>
<td>90.53</td>
<td>30.11</td>
<td>4300</td>
<td>14.1</td>
</tr>
</tbody>
</table>

Table 7.1: A few of the neutron monitors used for comparison.

### Advanced Composition Explorer

Measurements from the Advanced Composition Explorer (ACE) include solar wind parameters, interplanetary magnetic field, SEPs, particles accelerated in the heliosphere as well as from galactic regions beyond the solar system [12]. ACE is located at the L1 libration point, the Earth-Sun gravitational equilibrium point. It is about $1.5 \times 10^6$ km from the Earth and $148.5 \times 10^6$ km from the Sun. For a solar wind with a regular speed of $\sim 400$ km/s, the effects observed at ACE are experienced on the Earth about 1.04 hours later (table 7.1). Therefore, the physical quantities measured by ACE closely represent the physical conditions near the Earth. Table 7.3 lists the measurements used.

<table>
<thead>
<tr>
<th>Travel location</th>
<th>Distance [km]</th>
<th>Time for SW speed 400 km/s</th>
<th>Time for SW speed 600 km/s</th>
<th>Time for SW speed 800 km/s</th>
<th>Time for SW speed 1000 km/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun to ACE</td>
<td>$1.5 \times 10^5$</td>
<td>4.3 d</td>
<td>2.86 d</td>
<td>2.15 d</td>
<td>1.72 d</td>
</tr>
<tr>
<td>ACE to Earth</td>
<td>$1.5 \times 10^6$</td>
<td>1.04 h</td>
<td>0.69 h</td>
<td>0.52 h</td>
<td>0.42 h</td>
</tr>
</tbody>
</table>

Table 7.2: Travel times of the solar wind. Here “d” and “h” refer to days and hours respectively.
for comparison in this study. Parts of comparison include data from OMNIWeb [30],

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Measurement</th>
<th>Particles</th>
<th>Range of measurements</th>
<th>Collecting power</th>
</tr>
</thead>
<tbody>
<tr>
<td>SWEPAM</td>
<td>flux and</td>
<td>electrons, protons, alpha ions</td>
<td>&gt; 0.26 keV to &gt; 36 keV</td>
<td>0.397 cm² sr</td>
</tr>
<tr>
<td>EPAM</td>
<td>flux and elemental composition</td>
<td>electrons, ions</td>
<td>&gt; 30 keV to &gt; 50 keV</td>
<td>0.48 cm² sr</td>
</tr>
<tr>
<td>MAG</td>
<td>local IMF direction</td>
<td>ions</td>
<td>± 4 nT to ± 65 nT, 536 nT</td>
<td>0.24 cm² sr</td>
</tr>
<tr>
<td>SIS</td>
<td>high res. measurements</td>
<td>He to Ni</td>
<td>~10 - ~100 MeV/n</td>
<td>40 cm² sr</td>
</tr>
</tbody>
</table>

|               |                                      |                                |                                      |                  |
|               | of SEP, GCR, ACE composition         |                                |                                      |                  |

Table 7.3: Measurements used from ACE

which contains merged data from ACE, IMP-8, GOES, WIND [8], GEOTAIL [75] etc. experiments. Also compared but not included here are data from GOES (the Geostationary Operational Environmental Satellite [97] [107]) and Ulysses ([118]). GOES data were used to explore conditions in the magnetosphere and only Ulysses had measurements from the outer solar system during BESS-Polar I. In addition some geomagnetic activity conditions were compared.

Acknowledgment for data usage

I would like to thank the ACE SWEPAM, MAG, EPAM, and SIS instrument teams and the ACE Science Center for providing the ACE data. I acknowledge the Bartol Neutron Monitor network and the Izmiran neutron monitor database for their data. I would also like to thank the OMNIWeb, CDAWeb, Space Physics Interactive Data Resources at the National Geophysical Data Center (SPIDR/NGDC) for neutron monitor data (other than Bartol neutron monitors), data for geomagnetic and solar activity, and some solar wind plasma and particle data.

The next section gives a brief overview of solar activity during BESS.
7.2 Solar activity during BESS-Polar I

The Sun was mainly quiet during BESS-Polar I flight, which took place nearing a solar minimum; a period of Carrington rotation 2024. A few small solar activities occurred during this period. This section presents some overall solar activity conditions shortly before and during the BESS-Polar I flight.

7.2.1 Sunspot number

Sunspots are magnetic regions on the Sun that appear as dark spots on its surface. They usually appear in pairs or pairs of groups with opposing polarity of magnetic field. The sunspot numbers are counted by first counting the number of sunspot groups and then number of sunspots in individual groups. Sunspot numbers are indicative of the strength of solar activity. Figure 7.2 shows the sunspot numbers during the BESS flight.

![Sunspot numbers during BESS-Polar I](image)

Figure 7.2: Sunspot numbers during BESS-Polar I. [7]

The solar activities that may have affected the BESS flux: Formation of a coronal hole started around December 10. A high speed solar wind stream (HSSWS) originating from from this coronal hole arrived near the Earth on December 16. The Earth remained in this HSSW from December 17 - 19 (revisited later in this chapter). Figure 7.3 shows a few images of the Sun marking the above observations [6].
Next section discusses the solar energetic particle event that started shortly before the BESS-Polar I launch.

7.2.2 Solar energetic particles event

A “high energy multiple eruption” solar energetic particle event was recorded in December 2004 [4], [34], [4]. This first eruption from this SEP (figure 7.4) reached the Earth around December 5. Protons and helium energies were measured up to $\sim 69.1$ MeV/n (perhaps the energy limits of instruments) but this SEP event may have included particles of somewhat higher energies.

BESS-Polar I started at the tail end of the first SEP intensity increase, as observed at ACE. There was another small increase in SEPs on December 12. Therefore, while this SEP did not contaminate BESS measurements, it may have enhanced the IMF, which in turn would affect the cosmic rays. A related image (figure 7.5) from POES satellite [102] shows an increase in electron density during this period, such an increase is a characteristic of SEP events [81]. The next section summarizes geomagnetic conditions during BESS-Polar I.
Figure 7.4: High energy multiple eruption SEP event starting on Dec 5, 2004. [12]

Figure 7.5: Increased electron density from POES for December 13-18. [102]
7.3 Geomagnetic conditions during BESS-Polar I

The geomagnetic conditions are also affected by any solar activity. A strong geomagnetic activity can influence regions near the Earth and impact the particle fluxes, especially at low energies. This section lists a few of the geomagnetic indices during the BESS-Polar I flight. These indices represent the geomagnetic conditions and are defined below [18] [14] [74]:

The DST (Disturbance Storm Time) equivalent equatorial magnetic disturbance indices are derived from hourly scalings of low-latitude horizontal magnetic variation. They show the effect of the globally symmetrical westward flowing high altitude equatorial ring current. A great storm occurs when DST \(\leq -100\) nT, a moderate storm occurs when \(-100\) nT \(<\) DST \(\leq -50\) nT, and a weak storm occurs when \(-50\) nT \(<\) DST \(\leq -30\) nT [41].

**K index** is a quasi logarithmic index of geomagnetic activity relative to an assumed quiet day for the recording site. These indices represent the range of variation of the more unsettled horizontal component of the magnetic field converted into disturbance levels. K indices range from 0 (quiet) to 9 (greatly disturbed) in 28 steps. The arithmetic mean of the K values scaled at the 13 subauroral observatories between 44° - 60° gives the global Kp index [27] [96]. Kp values from 0 - 4 indicate conditions below magnetic storm [80].

The **Ap index** is a measure of the general level of geomagnetic activity over the globe for a given (UT) day. Ap index is derived from the measurements of the variation of the geomagnetic field due to currents flowing in the Earth’s ionosphere and, to a lesser extent, in the Earth’s magnetosphere, made by several stations world-wide [108]. When the average Ap rises above an arbitrary threshold (usually 40), a major magnetic storm is considered to be in progress [106].
**Cp and C9 indices** provide a qualitative estimate of overall level of magnetic activity for the day, determined from the sum of the eight daily Ap amplitudes. Cp ranges from 0 (quiet) to 2.5 (highly disturbed) in steps of one-tenth. A conversion of the Cp index to one digit between 0 and 9 results in C9 index. C9 = 5 has been suggested as the lower limit for a major magnetic storm [92].

It has been suggested that when Ap is between 15-48 and Kp is between 3-5, the geomagnetic conditions move from “unsettled” to “active” or “major storm” [119].

Figure 7.6 shows that some of the geomagnetic indices reached values close to the values defined as the geomagnetic storms. Hence a comparison of Kp, Ap, and storm conditions suggests:

1. Around Dec 12-13, the geomagnetic conditions were elevated to “active” and even to a “major storm” briefly (for a few hours). DST values showed it to be a “moderate storm”. This has been reported to be associated with the arrival of a gusty solar wind stream [6].

2. Between Dec 17-19, the geomagnetic conditions were elevated to “Active”.

3. Things were “quiet” for the next couple of days.

It is clear that geomagnetic conditions were disturbed and mild geomagnetic storm conditions were present but there was no major geomagnetic storm. Around December 12 Kp was closer to 4 and 5. Around December 17 the Ap and Kp indices were higher; almost reaching its limits for magnetic storm conditions (figure 7.6).

From a study of 1400 Forbush decrease events Belov et al. concluded that the average magnitudes (≤ 1.5%) of Forbush decreases are observed during magnetic storms (Kp = 5) [37]. So it is possible that the cause of the observed cosmic ray decrease during whose recovery BESS was launched, may have contributed to the enhanced geomagnetic conditions.

Next sections compare our time varying proton fluxes with data from other experiments.
Figure 7.6: Geomagnetic indices December 2004 (data from SPIDR [7]).

(a) DST Index, December 2004
(b) A_p Index, December 2004
(c) C9 Index, December 2004
(d) K_p Index, December 2004
7.4 Comparison with neutron monitor data

Although data from all the neutron monitors listed in section 7.1.1 were used, for simplicity this chapter only shows count rates of McMurdo (near the geomagnetic south pole), South Pole (the geographic south pole), Thule (the geomagnetic north pole), and Inuvik (near Thule) neutron monitors in figures 7.7 and 7.8.

A study of the data from the neutron monitors, situated at different locations on the Earth, shows that similar to BESS proton fluxes (chapter 6), the count rates from these neutron monitors exhibit a decrease during December 13-14, an increase from December 14 to 17 or 18, followed by a stabilizing, quasi-periodic behavior, which has a minimum and a maximum during each day. Figure 7.9 shows normalized count rates for a few neutron monitors; the count rates for each neutron monitor have been normalized by its count rates of December 17.5, 2004. December 17.5 was selected because it falls somewhere in the middle of the BESS-Polar I flight and it is around this time that the cosmic ray data started to stabilize. The McMurdo and Thule neutron monitors, being near the geomagnetic poles, did not observe the periodic fluxes.

The next section presents a more detailed where the normalized neutron monitor count rates were averaged into the 4-hour time intervals used for BESS-Polar I data in chapter 6.
Figure 7.7: Count rates: McMurdo and South Pole neutron monitors.
Figure 7.8: Count rates: Thule and Inuvik neutron monitors.
Figure 7.9: Neutron monitor count rates, normalized to their respective Dec 17.5 count rates. The legend on the plot lists the names of neutron monitors.
7.4.1 4-hour averaged neutron monitor count rates

McMurdo and South Pole neutron monitors were used for this comparison. The great circle distances of BESS payload (using only the Latitude and Longitude) from the geomagnetic and geographic south poles as function of time are shown in figure 7.10. After the first few days the BESS payload floated closer to the geographical south pole than the magnetic south pole and similarly, the BESS payload was closer to the South Pole neutron monitor than the McMurdo neutron monitor. Therefore, the physical conditions near the South Pole were a better representative of the conditions near our payload than those at the McMurdo neutron monitor. The information and coordinates of poles were taken from the Australian Antarctic Division [2] and Kyoto World Geomagnetic Data Center [9].

Each neutron monitor has a response function. For cosmic ray spectra, this function has a maximum that can be used to estimate the particle energy “observed” by the detector. Figure 7.11 shows the response function for the South Pole neutron monitor during solar minimum and solar maximum. Full width at half maximum (FWHM) of this response function is in the range of rigidity \( \sim 2 - 10 \) GV, which is close to \( \sim 2.0 - 10.0 \) GeV in energy range. BESS proton fluxes for energy interval 1.0 - 10.0 GeV are compared with the McMurdo and South Pole neutron monitors in figure 7.12. McMurdo neutron monitor does not show a pronounced periodicity although hints of such pattern are present, it also does not show the “dip” of December 17 but has a small kink at that point in time. The South Pole neutron monitor count variations are remarkably similar to our proton fluxes. The “dip” is not as pronounced as in our flux but that time is marked with the first decrease of the periodic behavior.

This section established that the cosmic ray proton intensity variations observed by BESS-Polar I were also observed by neutron monitors located worldwide. The neutron monitor measurements are independent of BESS-Polar I measurements and of each
(a) BESS payload from magnetic south pole (Longitude: 138.3, Latitude: -63.5) and geographical south pole (longitude: 0.0, Latitude: -90.0).

(b) BESS payload from the McMurdo (Longitude: 166.6, Latitude: -77.9) and South Pole (Longitude: 0.0, Latitude: -90.0) neutron monitors.

Figure 7.10: Distance of BESS payload from the poles and neutron monitors.
The next sections explore physical conditions in the heliosphere.

### 7.5 Comparison with solar wind plasma data

This section presents the parameters characterizing the solar wind plasma during BESS-Polar I. Unless otherwise specified, the data are from ACE.

#### 7.5.1 Solar wind plasma parameters

Figure 7.13 shows the speed, proton density, temperature, flow pressure, azimuth angle etc. data from two days prior to the launch of BESS-Polar I to explore space conditions that may have affected BESS proton fluxes. The initial observations in relation to BESS measurements are summarized in this sections and the next.
(a) BESS p flux and McMurdo NM.

(b) BESS p flux and South Pole NM. These are very similar, the payload was floating close to the South Pole neutron monitor.

Figure 7.12: Normalized BESS proton flux (1.0 - 10.0 GeV) and normalized neutron monitor count rates from McMurdo and South pole neutron monitors. Each point corresponds to a 4-hour average.
ACE observed a higher **Solar wind plasma speed** on December 11-12, prior to the launch of BESS-Polar I. Overall the speed remained more or less stable from December 13-16 with a variation of ± 25 km/s. BESS proton flux increased during this period (figures 6.21, 6.22, 6.23, 6.24, 6.25, 6.26, 6.27). Another high speed solar wind stream arrived around December 17.

**Solar wind proton density** dropped on December 13, stayed stable around 5 particles cm$^{-3}$ from December 13-16. Shortly before December 16, there was an increase in density to ~ 20 particles cm$^{-3}$. This is the “transition region” for BESS proton flux. Then the density decreased and stayed stable; this duration coincided with the stabilizing quasi-periodic proton flux in BESS.

**Solar wind proton temperature** increased on Dec 12 but was lower around December 13. Two main temperature changes occurred during BESS, one lasting from December 13-15, and another lasting between December 16-20. The biggest increase occurred between December 16-17, following which the temperature stayed at a higher value and gradually came back to its lower value after about 4 days.

The increase and decrease in the **solar wind flow pressure** correlated with the increase and decrease of proton density observed during the same periods.

For the purpose of this discussion the **solar wind flow azimuth angle** of the IMF can be defined as the angle between the projection of the IMF vector onto the equatorial plane and the radial direction, taking positive in a right handed sense. Azimuthal angle of zero would correspond to a radial motion and its deviation from zero shows how tightly/loosely the Parker spirals are wound.

### 7.5.2 Interplanetary magnetic field

The magnitude and components of the IMF (IMF is referred to as B) are shown in figure 7.14. The overall structure of the IMF had two increases during BESS, one between December 12-14 and another between December 16-18. There was an increase (to ~
Figure 7.13: Solar wind parameters (data from [12] [30])
Figure 7.14: Magnitude and components of the IMF. By and Bz are higher during December 12-14, all show a dip around Dec 13. Bx and Bz have greater fluctuations during December 15-18.
15 nT) in B magnitude around Dec 11-13, it decreased around Dec 14 and stayed at a lower value till December 16, following which another increase occurred (to \( \sim 10 \) nT) and then the magnitude of the IMF decreased on December 18. It stayed lower (\( \sim 5 \) nT) through the remainder of the BESS flight. The individual components show variations around December 11-13 (rise in BESS proton flux at a rate of \( \sim 2\% / \text{day} \)) and some fluctuations from December 15-18 (rise of BESS proton flux slowed around December 17 to later stabilize).

In this initial comparison the solar wind plasma parameters show some correlation with observed behavior of BESS proton flux but there appears to be no direct and easy explanation for the features in our fluxes. Therefore, a detailed analysis must be made to understand the three main features of BESS proton flux. The next step is to explore possible causes of the observed characteristics of the solar wind and IMF.

### 7.6 How to proceed with interpretation?

An exploration of processes that took place in the heliosphere near the Earth during the flight will help interpret possible causes of the features observed in our proton flux. The main events observed by ACE were an SEP event, a high speed solar wind stream, and an increase in the magnitude of the IMF.

Studies have shown that a high speed solar wind does not always produce a decrease in the cosmic ray intensity [19] [60] [43] [38] [39]. Even very high speed solar wind may produce small or no decrease; cosmic ray variations of different magnitudes have been observed for the same solar wind speed. Similarly, although high IMF magnitudes are generally associated with CR decreases [22], they do not always contribute to a CR decrease. Therefore, while cosmic ray decrease is related to individual B enhancements, the correlation between cosmic ray intensity and B magnitude can be poor [104] [91]. Sometimes a slow moving magnetic disturbance causes a bigger decrease in CR intensity.
than a fast moving region [23] [64] [56] [40]. Barouch and Burlaga considered a few cases of Forbush decreases and less intense variations using a magnetic blob; they showed that particles can be swept away faster than the blob advances [22]. Therefore, it becomes important to understand the nature and cause of the magnetic field enhancement in order to understand the CR variations [91].

The next section explores the BESS proton flux in relation to the observed SEP event and the high speed solar wind stream.

### 7.6.1 SEPs near BESS

Neutron monitor count rates from the McMurdo and South Pole stations for December 3-22 (figure 7.15) decreased around December 5. This corresponds to the time when a big SEP event was observed at ACE (figure 7.4). Then the cosmic rays started to recover but around December 12-13 there was another decrease corresponding in time to a small SEP flux increase. After this the cosmic rays started another recovery, during which BESS was launched. So the physical process associated with BESS observations appear to be somewhat related to this SEP event. SEPs, which generally contain particles of much lower energies than BESS is designed to measure, can modify the IMF, cause heating, and are sometimes associated with magnetic clouds\(^1\) and merged interaction regions (MIRs). Magnetic clouds and merged interaction regions have been observed to cause transient variations in GCRs.

### 7.6.2 High speed solar wind stream

Reports on solar activity suggest that the high speed stream from the coronal hole (figure 7.3(c)) arrived at the Earth around December 16-17. A high speed solar wind stream adjacent to a slow speed stream can be associated with a corotating interaction region (CIR). Such regions have been observed to cause cosmic ray decreases [6]. Therefore,

\(^1\)Ejections from the Sun.
Figure 7.15: Comparison of McMurdo and South Pole neutron monitor count rates with the SEP event observed at ACE. ACE observed a big increase in SEP around December 5 and then a smaller one around December 12. BESS duration is marked with vertical blue lines.

It is important to explore the local heliosphere for any such interaction regions shortly before and during the BESS flight.

The next section provides a brief description of such regions.
7.7 Physical structures that cause variations in cosmic ray intensities

A variety of interplanetary structures such as magnetic loop/cloud, ordered field topology, shock and compressed field region of ambient plasma (sheath) preceding the transient ejecta from the sun, as well as stream-stream interaction can cause enhancement in the interplanetary magnetic field [91]. A few such structures are defined here.

7.7.1 Magnetic clouds

The idea of magnetic clouds was introduced by Burlaga in 1981 [16] [25]. A magnetic cloud is a solar ejection in which:

(i) the magnetic field strength is enhanced with respect to an ambient value,

(ii) the magnetic field vector undergoes a large rotation, and

(iii) the proton temperature is lower than average.

Magnetic clouds and associated structures at 1 AU have been found to be associated with Forbush decreases in cosmic ray intensities. Based on their characteristics, magnetic clouds are classified as listed in the table 7.4 [114]. Magnetic clouds are also known as the interplanetary coronal mass ejections (ICME) where the Beta $\beta$, of the solar wind plasma is low [121]. $\beta = p/(B^2/2\mu_0)$ is the ratio of particle pressure and magnetic field pressure, here $p$ is the particle pressure.

7.7.2 Merged interaction regions

When slow and fast speed solar wind streams occur from coronal holes (like during BESS-Polar I), a merged interaction region (MIR) is formed. As the solar wind of high speed stream traverses the interplanetary regions, it pushes the slower wind that is ahead. This causes changes in the IMF and during these changes the variance of $B$ fluctuates more violently than usual. Such fluctuations seem to precede the high speed
A magnetic cloud moving with the ambient solar wind.

A magnetic cloud can move faster than the solar wind and form shock/sheath structure.

A magnetic cloud that can be “pushed” by the faster moving solar wind from behind thus forming an interaction region between the two.

A magnetic cloud can be associated with a shock followed by high speed streams.

A transient decrease with a fast recovery.

A fast decrease and a slow recovery.

A slow decrease and a slow recovery.

A slow decrease with a very slow recovery.

<table>
<thead>
<tr>
<th>Characteristics of magnetic cloud</th>
<th>Behavior of the associated cosmic ray variations</th>
</tr>
</thead>
<tbody>
<tr>
<td>A magnetic cloud moving with the ambient solar wind.</td>
<td>A transient decrease with a fast recovery.</td>
</tr>
<tr>
<td>A magnetic cloud can move faster than the solar wind and form shock/sheath structure.</td>
<td>A fast decrease and a slow recovery.</td>
</tr>
<tr>
<td>A magnetic cloud that can be “pushed” by the faster moving solar wind from behind thus forming an interaction region between the two.</td>
<td>A slow decrease and a slow recovery.</td>
</tr>
<tr>
<td>A magnetic cloud can be associated with a shock followed by high speed streams.</td>
<td>A slow decrease with a very slow recovery.</td>
</tr>
</tbody>
</table>

Table 7.4: Magnetic cloud structures and associated cosmic ray decreases [114].

stream. In such interaction regions, the most powerful eruptions sweep up the slower preceding transient and create MIRs. The interaction between high speed plasma cloud and ambient field of solar wind forms a turbulent interaction region (TIR). The magnetic turbulence of a region, the characteristic of a TIR, is measured by the variance of the magnitude of the IMF. A decrease in cosmic ray intensity occurs while the turbulence is high and the cosmic rays can start recovery after the turbulence has passed even if the magnitude of IMF is high [19].

7.7.3 Corotating interaction regions

As discussed in Chapter 3, the solar wind moves in Parker spiral. Streamlines in faster solar wind follow spirals that are less tightly wound [82] [73] [104]. If there is a slow stream adjacent to a fast stream, the fast stream tries to overtake the slow stream but its motion is constrained by the magnetic field. As a consequence, the leading edge of a fast solar wind stream collides with the slower solar wind ahead of it. This results in a build up of density, pressure, and magnetic field in front of the high speed solar wind stream, creating a compressed region towards the front. A rarefied region behind the high speed stream is created because this high speed stream is moving ahead faster.
than the slower stream behind it. As the solar wind moves farther away, the pressure continues to build within the streams and shock fronts can be generated in both the forward and reverse directions. The plasma, bound by the two shocks, is an interaction region, known as a corotating interacting region which lies approximately along the Archimedian spiral [100].

CIRs are prominent features of the solar wind during the declining and minimum phases of the 11-year solar cycle. The boundary between the slow and fast stream regions is called the stream interface. Typical characteristics of the interface include a relatively abrupt decrease in plasma density, increase in plasma proton temperature, and the solar wind speed. The interface tends to deflect the solar wind that is ahead of it in the sense of rotation (West) while the solar wind that follows is deflected in the opposite direction (East); this causes a reversal in azimuthal angle of solar wind flow.

### 7.7.4 Compton-Getting effect

This was first explained by Compton and Getting in 1935 as a possibility that the motion of the Galaxy (and hence that of the Earth) through space may affect the cosmic ray intensities [29]. The cosmic rays arrive isotropically near the Earth. The solar magnetic field follows an Archemdean spiral structure and the cosmic rays, measured within the energy range of BESS, tend to be entrapped in this co-rotating spiral structure. The relativistic effects caused by the motion of guiding centers of trapped particles, i.e., tendency of cosmic rays to participate in the co-rotation motion of the solar magnetic field, can cause diurnal variations in the cosmic ray intensities [13].

The next section explores possibility that a magnetic cloud or a CIR during BESS may be associated with the observed variations in our proton flux.
7.8 Suggested physical interpretation

Based on the neutron monitor and solar wind plasma data, some physical interpretations are proposed for the observed features in the BESS-Polar I proton flux.

7.8.1 Feature I: rising flux at the beginning of the flight

Due to presence of high speed solar wind stream and SEPs, the near-Earth region in this duration was explored for presence of a CIR interface and a magnetic cloud, and turbulent interaction region. The higher speed stream (of December 12) in the solar wind may have swept away some particles resulting in the observed decrease of flux, as seen in the neutron monitor data (figure 7.15).

From figure 7.16 it is clear that the magnitude of B increased, Bz changed direction, and the proton temperature was lower (∼0.25 x 10^5 K as compared to a typical value of ∼1.2 x 10^5 K). These are characteristics of a magnetic cloud and hence there is a possibility that a magnetic cloud may have caused the decrease in cosmic rays around December 12-13, before the start of BESS flight.

The solar wind plasma data (figure 7.17) indicate that there was a CIR around December 12-13. It was characterized by an increase in solar wind speed, increase in the IMF magnitude, increases in the flow pressure, increase in the proton temperature, a reversal in the flow azimuthal angle, and a sharp decrease in the particle density.

In addition, during December 12-13, the IMF increased and the turbulence in the IMF was high, as observed by the variance in the IMF magnitude. This resulted in the cosmic ray decrease decrease observed by the neutron monitors. The IMF stayed at a slightly higher value but the turbulence had passed. Thus the cosmic rays started to recover from December 14th. Such correlations are characteristics of MIRs or variations caused by magnetic clouds.

Hence, we can infer that a CIR or a magnetic cloud or a combination of both of these
Figure 7.16: Solar wind parameters during BESS-Polar I. High B mag, Bz rotation, low temp, low plasma beta are conditions for a magnetic cloud (between the vertical green lines). There is a corresponding decrease in neutron monitor counts.
structures may have been responsible for the CR decrease of around Dec 12-13. As this interface of slow and fast stream passed, cosmic ray flux started to recover. BESS was launched during this recovery and this increase is seen as the Feature I.

7.8.2 Feature II: the “transition region” around December 17

Figure 7.13 shows that a slow solar wind (∼ 375-400 km/s) was followed by a fast solar wind (∼ 650 km/s) around December 16-17 near the Earth. Figure 7.18 shows that this could be another small CIR interface characterized by a higher solar wind speed,
an increased IMF magnitude, a higher flow pressure, an increased proton temperature, and a reversal in azimuth angle, but there was no sudden decrease in the particle density in the solar wind. Although CIRs are usually characterized by a sharp decrease in the proton density, the interface is not always sharp [104]. Around Dec 17 both B magnitude and variance in B were high; this is an indication of an interface between slow and fast solar wind streams. I suggest this is a weak CIR because it exhibits behavior somewhat similar to that of a CIR reported by Forsyth and Gosling [73], where the CIR interface was not sharp.

This weak CIR interface corresponds to the dip in CR on December 17, which is a few hours delayed after the disturbance but a CIR interface can have an onset slightly before or after the turbulence in magnetic field [104]. This cosmic ray intensity depression lasted less than a day but such behaviors have been reported earlier where no CR depressions were observed under similar conditions so it is not required that a CIR causes a big depression in the cosmic ray intensities.

The peak in place of this dip for the lowest energies (below $\sim 1.0$ GeV) may be explained by the trapping of the low energy particles in the turbulence. Then the high energy “dip” marks a clear onset of diurnal variations. According to Gold’ Tongue model the low energy particles get trapped in the “tongue” or a magnetic disturbance, the high energy particles are deflected/scattered from it [77]. This causes an increase in the low energy flux and a depression of higher energy flux. This coincides with another possible explanation for this feature in conjunction with a turbulent interaction region [19]. During the “transition region” the magnitude and turbulence in IMF were high and its components had a greater degree of fluctuations than was present before or after this period. BESS observed a decrease in proton flux with a dip for energies $\sim > 0.87$ GeV. After December 17-18, the turbulence passed and no further decrease in BESS p flux was observed although the IMF magnitude and solar wind speeds were still high. The BESS p flux started to recover.
Figure 7.18: Was there a CIR interface around Dec 17?
A very small increase in SEP intensities was seen at ACE around December 17. This may be another possible factor affecting the flux around December 17. If this was a contributor to the dip, it may be explained using some of Cane’s results on Forbush decreases, according to which a less energetic ejecta causes a cosmic ray decrease of a small amplitude and short duration [26]).
7.8.3 Feature III: periodic behavior

The quasi-periodic pattern was present in the proton flux and neutron monitor data before December 17. However, up until then the flux was rising at a greater rate than after December 17 and the physical conditions seemed more complex. Beginning on December 17 we clearly see the periodic behavior of the flux and it is easier to separate this pattern from other effects in the flux. Comparison of the time progression of our proton flux with neutron monitor data (which observe diurnal variations due to their corotation with the cosmic ray streams) suggests that the BESS proton flux has diurnal variations. The similarity between BESS and the South Pole neutron monitor data is striking (figure 7.12(a)). The periodic behavior of the BESS proton flux has an amplitude that decreases with increasing energies, as expected according to Borie [58] and Mailyan [87]. The lower energy proton fluxes showed a higher amplitude while the higher energy fluxes had lower amplitude of this variation.

Some studies suggest that quiet days are better suited for studies of daily variations [63]. Periodic behavior was observed in our proton flux during low geomagnetic activity, i.e., after \( \sim \) December 16 when Ap was small. During the relatively quiet period, after the turbulence and effects of SEP and the high speed solar wind stream had passed, BESS-Polar I observed the diurnal variations.

The diurnal variations in our proton flux are small in amplitude but quite well correlated with the neutron monitors. These diurnal variations are result of the Compton-Getting anisotropy.

The next section presents a summary of comparison and suggested interpretations.

7.9 Summary

A detailed comparison of our proton fluxes and various neutron monitors around the world gives us high confidence that observed transient variations in our data are real.
Comparisons with the parameters characterizing the nearby heliospheric regions shows some correlations between the behavior of observed proton fluxes and the solar wind parameters. A comparison of solar wind speed, proton density, temperature, flow pressure was carried out to explore the possibility that a weak CIR during BESS observations caused some variations in proton flux. An increase in the intensities of SEPs was observed near the Earth around December 5, 2004 and appears to have contributed to physical conditions that cause the cosmic ray flux variations. Exploration of the solar wind data indicates a possibility that a magnetic cloud and merged interaction regions, or a combination of these, may have contributed to the CR decrease on whose recovery phase BESS-Polar I was launched.

BESS-Polar I observed effects of more than one physical process. The effects of coronal mass ejections and coronal holes are rarely seen purely by themselves [37]. BESS measurements are clearly very sensitive and reflect the local heliospheric conditions.

These facts make our data very useful for investigation of physical processes near the Earth and validation of models for space weather predictions. Another interesting aspect is that a high speed solar wind stream was introduced from coronal holes, effects of this stream are observed in our data. Perhaps our data can provide some needed constraints to test models of transient effects of such streams ([104] and references therein), models of CIRs (e.g. [83]) and models to predict the space weather [20], [24].

Explanations and models of diurnal variations (e.g., [46], [44]) suggested in the literature may find our data useful because BESS observed diurnal variations. Although these variations have been well known for the last several decades, they have been primarily observed by ground-based detectors which, unlike direct measurements from BESS, provide secondary measurements. BESS measurements may be useful in testing the effects of SEPs (and perhaps theoretical models of their propagation) and their connection to magnetic clouds [42], [48], [57]. Models of recovery of cosmic ray decreases can be tested using BESS-Polar data (an example: [47]).
An initial analysis of BESS measurements vs. McMurdo and South Pole neutron monitor measurements shows that there appears to be a linear correlation between the two. A more detailed analysis can be carried out to derive any correlation factors which may prove to be useful for these neutron monitor stations especially as neutron monitor response function may change over time [50].

Conclusions of the research work carried out for this dissertation and possible future prospects are presented in the next chapter.
Chapter 8

Conclusion and future studies

A study of transient variations in cosmic ray proton intensities has been carried out using BESS-Polar I data. The energy spectra of protons at energies 0.1 - 100.0 GeV were measured for the duration of whole flight, daily and 4-hour intervals and were then explored for variations in daily and hourly (4-hour average) time intervals. Energy dependence of observed variations was examined by studying the behavior of the flux at different energy intervals for the same time frame. As explained in chapters 1 and 3, BESS makes precise measurements in a wide energy range due to its sensitivity and greater geometrical acceptance compared with similar experiments. These measurements clearly reflect the conditions in the local heliosphere and can be used by theoretical models to test effects of magnetic clouds, high speed solar wind stream, and corotating interaction regions etc. on the cosmic ray fluxes.

Measured proton fluxes and error bars are presented. As discussed in chapter 6, the BESS proton flux increases at the beginning, has a transition region characterized by a peak at lower energies and a dip at higher energies, and a quasi periodic flux on top of a slowly rising flux during the last few days of the flight.

There are variations in proton fluxes at the few-1% level on few hour time scales. To our knowledge these are the first direct satellite or balloon measurements at this
precision. While the ground-based experiments have observed such variations, they mainly measure secondary cosmic rays. The space-based experiments are limited by size and hence, have smaller geometrical factor, thus limiting their precisions at these time scales. The balloon experiments with comparable measurements either operate at much higher energies, did not explore for transient variations of cosmic rays or did not have long duration balloon flights.

Analysis of rigidity spectrum will help understand the rigidity and therefore, mass dependence of these variations. A time variation study of helium from BESS-Polar I, when combined with proton studies, will provide charge dependence of the observed transient variations.

In this analysis the lowest energy particles (E \sim 200\ MeV) were not included, these are particles that reached the MTOF but did not reach the LTOF. Analyzing those particles would help understand the short-term variations at the lowest energies and would provide extended data set.

Our atmospheric corrections have some limitations at energies below \sim 0.3\ GeV such that the fluxes at the top of the atmosphere do not normalize for different atmospheric overburdens. An improved atmospheric correction will help.

Detailed comparisons with the neutron monitor data confirm that the observed variations are real. Comparisons with solar wind plasma data show some correlation between the behavior of the BESS proton flux and nearby physical conditions in the interplanetary solar wind plasma. Several physical processes took place in the local heliosphere during the BESS-Polar I flight, including arrivals of solar energetic particles and high speed solar wind streams originating at coronal holes. The SEP event suggests enhanced magnetic field, heating of the solar wind, and possibility of magnetic clouds. Adjacent fast and slow solar wind streams indicate corotating interaction regions. The observed features in the time progression of BESS proton fluxes may have been caused by a complex combination of processes associated with these plasma structures. The
suggested interpretations are based on solar wind plasma data and literature on previous studies of similar interplanetary structures. BESS data can be used to test models of recovery phase of Forbush decreases. This study has opened another area of analysis for BESS and our measurements can be used to explore conditions in the heliosphere, and validation of space weather models.

Finally, it must be noted that the second polar flight, BESS-Polar II was longer with overall improved performance of the detector. An analysis of BESS-Polar II data will be completed and presented elsewhere. An initial look at BESS-Polar II data reveals it observed some transient variations. For BESS-Polar II we have more experiments (e.g. STEREO) to compare conditions in the outer heliosphere. A study of data from the two flights, comparing observed features physical structures in the local heliosphere, will be of immense help in improving our understanding of physics of transient variations in cosmic ray intensities.
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