ENERGETIC PARTICLES IN THE MAGNETOSHEATH
AND THEIR INFLUENCE ON MAGNETOSHEATH
PLASMA AND MAGNETIC FIELD

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MANÝETÝK ÖRTÜDEKİ YÜKSEK ENERJÝLI PARÇACIKLAR VE BUNLARIN MANÝETÝK ÖRTÜ PLAZMASI ÍLE MANÝETÝK ALANINA ETKÝSİ

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In this study, we searched for the effects of high energy particles on the solar wind and magnetosheath field and plasma using Interball-1 spacecraft measurements from 1995 to 1998. While we do not see any clear relation between the high energetic particles and density and magnetic field in the magnetosheath, a decreased density and magnetic field characterizes the solar wind in the presence of energetic particles. These results agree with the findings of the previous studies. Decreased magnetic field and density imply a decrease in the solar wind pressure hitting on the magnetopause. Thus, the magnetopause boundary expands or shrinks depending on the presence or absence of the high energy particles. This local, back-and-forth oscillatory boundary motion, in turn, drives waves, field aligned currents and bursts of precipitating particles. Energy and momentum extracted from the solar wind as a result of this interaction between solar wind and high energy particles are transferred along the geomagnetic field lines into the Earth’s ionosphere and upper atmosphere where the extra energy alters the ionospheric and upper atmospheric processes.

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January, 2002
İstanbul

Filiz Türk
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<tr>
<td>amp</td>
<td>Ampere</td>
</tr>
<tr>
<td>AMPTE</td>
<td>Active Magnetospheric Particle Tracer Explorers</td>
</tr>
<tr>
<td>AU</td>
<td>Astronomic Unit</td>
</tr>
<tr>
<td>B</td>
<td>Magnetic field vector</td>
</tr>
<tr>
<td>Bz</td>
<td>z-component of magnetic field</td>
</tr>
<tr>
<td>cts</td>
<td>Counts</td>
</tr>
<tr>
<td>CCE</td>
<td>Charged Composition Explorer</td>
</tr>
<tr>
<td>eV</td>
<td>electron Volt</td>
</tr>
<tr>
<td>E</td>
<td>Electric field vector</td>
</tr>
<tr>
<td>ELF</td>
<td>Extreme Low Frequency</td>
</tr>
<tr>
<td>EPE F</td>
<td>Energetic Particle Flux from F-detector for protons</td>
</tr>
<tr>
<td>ExB</td>
<td>Drift velocity (Cross product of E and B)</td>
</tr>
<tr>
<td>f</td>
<td>Frequency</td>
</tr>
<tr>
<td>FTEs</td>
<td>Flux Transfer Events</td>
</tr>
<tr>
<td>GOES 5</td>
<td>Geostationary Orbiting Earth Satellite 5</td>
</tr>
<tr>
<td>GOES 6</td>
<td>Geostationary Orbiting Earth Satellite 6</td>
</tr>
<tr>
<td>GSE</td>
<td>Geocentric Solar Ecliptic</td>
</tr>
<tr>
<td>HFA</td>
<td>Hot Flow Anomalies</td>
</tr>
<tr>
<td>Hz</td>
<td>Hertz</td>
</tr>
<tr>
<td>IMF</td>
<td>Interplanetary Magnetic Field</td>
</tr>
<tr>
<td>IMP-8</td>
<td>Interplanetary Monitoring Platform-8</td>
</tr>
<tr>
<td>Interball</td>
<td>Spacecraft name</td>
</tr>
<tr>
<td>k</td>
<td>Boltzmann constant</td>
</tr>
<tr>
<td>keV</td>
<td>kiloelectron Volt</td>
</tr>
<tr>
<td>km</td>
<td>kilometer</td>
</tr>
<tr>
<td>LLBL</td>
<td>Low Latitude Boundary Layer</td>
</tr>
<tr>
<td>m</td>
<td>meter</td>
</tr>
<tr>
<td>mHz</td>
<td>megaHertz</td>
</tr>
<tr>
<td>MeV</td>
<td>Megaelectron Volt</td>
</tr>
<tr>
<td>MHD</td>
<td>Magnetohydrodynamic</td>
</tr>
<tr>
<td>n</td>
<td>Particle density per unit volume</td>
</tr>
<tr>
<td>nT</td>
<td>nanoTesla</td>
</tr>
<tr>
<td>Pc</td>
<td>continuous Pulsation</td>
</tr>
<tr>
<td>Pi</td>
<td>irregular Pulsation</td>
</tr>
<tr>
<td>Psa</td>
<td>Kinetic pressure</td>
</tr>
<tr>
<td>PFU</td>
<td>Proton Flux Unit ($#$/cm$^2$/s/keV/st)</td>
</tr>
<tr>
<td>SE</td>
<td>Solar Ecliptic</td>
</tr>
<tr>
<td>T</td>
<td>Temperature</td>
</tr>
<tr>
<td>ULF</td>
<td>Ultra Low Frequency</td>
</tr>
<tr>
<td>UT</td>
<td>Universal Time</td>
</tr>
<tr>
<td>V</td>
<td>Velocity</td>
</tr>
<tr>
<td>VLF</td>
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ENERGETIC PARTICLES IN THE MAGNETOSHEATH AND THEIR INFLUENCE ON MAGNETOSHEATH PLASMA AND MAGNETIC FIELD

SUMMARY

The coupling between the solar wind and the Earth’s geomagnetic field is the most outstanding problem of the solar-terrestrial environment. It is this coupling that extracts energy, mass and momentum from the solar wind and deposits down to the Earth’s ionosphere and upper atmosphere. In this study, we examine the interaction means in the presence of energetic particles in the solar wind and magnetosheath. In this framework, we investigate how the energetic particles alter and modify the solar wind and magnetosheath field and plasma characteristics. It has been shown that the transient events like moving interplanetary shocks, discontinuities, pressure pulses and hot flow anomalies as such all cause variations in the solar wind pressure. The boundary which is formed as a result of the balance between the solar wind dynamic pressure and Earth’s geomagnetic pressure can move back and forth in an oscillatory manner in response to these variations in the solar wind pressure. Pressure variations can be caused by several reasons. Presence of high energy particles is one of these reasons. By modifying the solar wind density and magnetic field, consequently the pressure, they give rise to boundary motion. Waves, field-aligned currents and precipitating particles then carry the solar wind energy, momentum and heat to the magnetopause to the upper atmosphere along the geomagnetic field lines. Additional heat and energy have important consequences on the structure of the ionosphere and upper atmosphere. Among these are the expansion of neutral atmosphere due to the erratic heating and density increase, which in turn cause strong drag forces on the low-Earth (LEO), high-Earth (HEO) and geostationary (GEO) orbiting satellites and spacecraft.

Interball-1 spacecraft was launched at an highly inclined elliptical orbit to study the high latitude solar-terrestrial environment in August 1995. It is designed especially for studying the energetic particle phenomena and their consequences in the solar wind, magnetosheath, and magnetospheric tail. Therefore, in this work, we take advantage of the high resolution, state-of-the-art measurements of plasma, magnetic field and energetic particles to study the energetic particle effects in the magnetosheath. By determining the Interball-1 magnetosheath intervals from 1995 to 1998, we analyse plasma, magnetic field and energetic particle data to determine the dayside magnetosheath plasma and field structure in the presence of high energy particles. For comparison purposes, we also studied the energetic particle effects on the solar wind as well.

In the literature, energetic particles in the upstream solar wind are found to decrease the magnetic field and plasma density. These depressed magnetic field and density are accompanied with peaks on both sides of the depression regions owing to the plasma expanding within them. In our data, we also see magnetic field and
plasma density in the solar wind decrease corresponding to increased energetic particle flux level. However, this relation is not very clear in the magnetosheath. It seems these structures are more common in the upstream solar wind than they are in downstream, i.e. magnetosheath. In the magnetosheath, we see that 60% of energetic particle events shows similar signatures in magnetic field and plasma density to those found in the upstream solar wind while rest of the 40% events presents no clear features. When the energetic particles are absent in the magnetosheath, the relation is clearer, and relatively increased fields and plasma densities characterize the downstream solar wind. On the other hand, times when energetic particles are present in the magnetosheath can be distinguished fairly easily in time series plots as both plasma and magnetic field become more disturbed and the fluctuations in these parameters increase at those times. Owing to the bow shock related processes, the magnetosheath itself is a highly turbulent region where the fluctuating magnetic field describes the region. The signatures found in the solar wind may be modified at the bow shock or by the local processes in the magnetosheath so that a clear relation can not be extracted. Duration of the events is also important. Previous studies showed that these events occur during the bursts of energetic particles, namely very high energy particle flux levels during a very short time interval on the order of seconds. We may need to look for the energetic particle bursts over some flux threshold to extract effect in the magnetosheath.

In this study, we show that the energetic particles alter the solar wind and magnetosheath field and plasma density. In the magnetosheath, the relationship between the energetic particles and magnetic field, and plasma density is not clearly described in our events. On the contrary, in the solar wind, a clear decreasing plasma density and magnetic field relation with increasing energetic particle flux is seen.
MANYETİK ÖRTÜDEKİ YÜKSEK ENERJİLİ PARÇACIKLAR VE BUNLARIN MANYETİK ÖRTÜ PLAZMASI İLE MANYETİK ALANINA ETKİSİ

ÖZET


Interball-1 uzay aracı çok yüksek eğimi, elips şeklinde bir yöntüye sahip olup, Yer Gezegeni-Güneş çevresinin yukarı enlemlerini incelemek üzere 1995 yılının Ağustos ayında uzaya fırlatılmıştır. Uyduanın en büyük özelliklerinden bir tanesi ve bizim de bu çalışmada avantajımız kullanıklarımız, çok yüksek resolutionu olması ve zamanının en modern plazma, manyetik alan ve yüksek enerjili parçacıkların yollar aletler ile donatılmıştır. Uzay aracı güneş rüzgarı bölgesi, "bow" shock manyetik örtü, manyetopoz, manyetik kuşruk, ve manyetosferin iç bölgelerini

Güneş rüzgarı ortamında, "bow" şokun güneş tarafında, yüksek enerjili parçacıkların manyetik alan ve yoğunluğu azalttığını görüyoruz. Bu azalış manyetik alan ve yoğunluk alanları, etraflarındaki plazmanın sıkıştırılması sonucunda iki tane pik ile beraber oluşmaktadır. Her ne kadar bu tanımlanan özellikleri "bow" şokun önündeki güneş rüzgarında bulmak çok yaygın ise de aynı özellikleri manyetik örtüsü içerisinde bulmanın çok yaygın olduğunu gördük. Manyetik örtü içerisinde yüksek enerjili parçacık olaylarınının sadece % 60’ı buna benzeyen bir ilişki göstermiştir ve geri kalan % 40’ında belirgin bir özellik bulmadık. Ancak, zaman serisi örneklerinde yüksek enerjili parçacıkların olduğu ve ya olmadığı zamanları belirlemek çok kolay olmaktadır. Şöyle ki, eğer yüksek enerjili parçacıklar yok ise parametreler son derece kararlı, çalkantısız, düz ve zaman zaman artan yoğunluk ve manyetik alan gösterirken, yüksek enerjili parçacıklar var olduğunda çok daha türbülanslı, yüksek salınımlar gösteren bir yapı almakta ancak bir ilişki saptanamamaktadır. Güneş rüzgarının “bow” şokta uğradığı ani değişimler nedeni ile manyetik örtünün kendisi zaten çok çalkantılı bir yapıya sahiptir. Aslinda manyetik örtüyün manyetik örtü yapısı özelliği bütün parametrelerde görülen yüksek genlikli çalkantılardaemon. Bu nedenle, yüksek enerjili parçacıkların manyetik örtü içerisindeki etkileri manyetik örtü içerisinde meydana gelen lokal olaylar veya manyetopozda meydana gelen olaylar veya “bow” şokta meydana gelen olaylar nedeni ile değiştirilebilirler. Ayrıca, manyetik örtü içerisinde, šoka uğramamış güneş rüzgarındaki gibi bir etkinin veya tanınabilir bir etkinin görülmesi çok kısa bir zaman içerisinde çok yüksek enerjili parçacık patlamaları (bursts) gerektirebilir.

Bu çalışmada, yüksek enerjili parçacıkların manyetik örtünün plazma ve manyetik alan yapısını değiştirdiğini gösterdik. İncelediğimiz yüksek enerjili olaylarımıza, manyetik örtüdeki manyetik alan ve yoğunluğun artan enerjetic parçacık akışı ile çok belirgin bir ilişki göstermediğini saptadık. Ancak bu iliskinin manyetik örtüden ziyade, şoka uğramamış güneş rüzgarında daha etkili ve yaygın bir şekilde oluştuğunu gözledik.
1. INTRODUCTION

1.1. Purpose and Importance of This Study

This study presents the results of a survey on the influence of energetic particles on the magnetosheath magnetic field and plasma, specifically the density. Changes in the solar wind dynamic pressure are known to drive magnetospheric and ground pulsations, magnetopause motion, magnetospheric magnetic field compressions, transient oscillations in the high latitude flows, field aligned currents and precipitating particles into the Earth's ionosphere and upper atmosphere. Among these, we discuss the magnetopause boundary motion owing to the variable solar wind pressure. Particularly, we are interested in the pressure variations caused by the energetic particles. In the following chapters, first we give both theoretical and observational background on the transient events appeared in the literature including the pressure variations. Then, we present our results on the energetic particles in the solar wind and magnetosheath, their relation to the magnetopause motion and compare them with those obtained from the earlier studies.

In Section 2, we review solar-terrestrial environment and geomagnetic regions, and coupling ways between the solar wind and magnetosphere-ionosphere-upper atmosphere. In Section 3, we give some background on the sources of the energetic particles, specifically on the foreshock as it is the main source of energetic particles in the upstream solar wind and also the one we are mostly interested in. In Section 4, we present our survey results using Interball-1 magnetic field and density measurements when the energetic particles are present in the magnetosheath. Section 5 summarizes and concludes our search and compares our results with the findings of earlier studies. Finally, we state our future work in which this work will form a basis.
2. SOLAR-TERRESTRIAL ENVIRONMENT

2.1. On the Solar-Terrestrial Coupling

Earth’s atmosphere is affected by the Sun in two ways. Figure 2.1 gives a sketch of this interaction. One is the electromagnetic interaction between the solar radiation and Earth’s neutral atmosphere. As a result, this interaction produces an ionized region in the Earth’s atmosphere extending from 50-60 kms to 2000 kms although there isn’t any universally accepted upper limit to its extent. The second type of interaction is the magnetic interaction between the solar magnetic field carried by the solar wind and the Earth’s geomagnetic field. Both interaction mechanisms alter and restructure the Earth’s magnetosphere, ionosphere, upper atmosphere, and eventually below (Figure 2.2). Different gaseous regions where these interactions occur including solar wind, magnetosphere, ionosphere and upper atmosphere are commonly called the solar-terrestrial environment or shortly the geospace. Since all the geospace regions are in direct contact (Figure 2.3), they interact, communicate and work together by adjusting their physical properties and dynamics to the new conditions, which are conveyed to them. It is unavoidable fact that one should take into account the interaction mechanisms operating between these regions in order to successfully solve the physical and dynamical problems in each region.

In this work, we will introduce a transient structure, which occurs in the magnetosheath. Magnetosheath is the last solar environment that the solar wind passes through before it diverts and flows around the magnetospheric obstacle. We are interested in these events because these structures move the location of the Earth’s magnetospheric boundary, the magnetopause. The magnetopause is the final frontier of the Earth’s natural environment where Earth-originated gas completely fills the region, with the exception of the most polar-regions. Transient phenomena occurring in the magnetosphere, magnetosheath and solar wind drives waves, currents and particle precipitation, along the geomagnetic field lines. Waves, currents and particle precipitation are the means of energy, mass, momentum, and heat transfer from one region to the other. Therefore, determining their source is one of
the important but at the same time complicated issues on the solar wind-magnetosphere coupling.

In the following sections, we review our solar-terrestrial environment (Section 2.2.), physical mechanisms operating in them and the interaction ways (Section 2.3).

2.2 Earth’s Solar-Terrestrial Environment: Geometry

Figure 2.3 gives a sketch of Earth’s solar-terrestrial environment in relation to each other consisting of solar wind, magnetosphere, ionosphere, and lower atmosphere. In terms of height, ionosphere and magnetosphere overlap with the Earth’s upper stratosphere, mesosphere and thermosphere where spatial trends in atmospheric temperature characterize the regions.

2.2.1. Sun, Solar Wind and Bow Shock: Figure 2.4 is an illustration for the solar-terrestrial coupling in three-dimensional view [Rycroft, 1989]. The Sun’s corona at a temperature of over one million Kelvins is the source of the solar wind plasma, a mixture of electrons and ions that is electrically neutral on average. The expanding supersonic solar wind, with a speed of one million kilometers per hour (400-500 km/sec), encounters the Earth’s intrinsic magnetic field. Earth’s magnetic field acts just like an obstacle in a supersonic wind tunnel. Upstream a bow shock is formed where the solar wind slowed down and bring into a speed with which it can smoothly flow around the magnetospheric body. In addition to the deceleration, solar wind is thermalized at the bow shock. Figure 2.5 shows the solar wind parameters at the bow shock. As seen in this figure, density, magnetic field, temperature and pressure (not shown) increase while velocity decreases at the bow shock.

2.2.2. Magnetosheath and Magnetopause: Passing bow shock, decelerated and thermalized solar wind fills a region called magnetosheath just before it interacts with the geomagnetic field lines. Magnetosheath is a turbulent transition region where shocked solar wind plasma flows around the magnetosphere. Due to the interactions at the bow shock, the magnetic fields in the magnetosheath become highly perturbed. In fact, it is the magnetic field fluctuations with high amplitude and high frequencies that characterize the magnetosheath. As the magnetosheath flow diverts around the magnetopause boundary, magnetic field lines within the
magnetosheath drape over the magnetospheric body. This shocked solar plasma flow compresses the geomagnetic field in the dayside magnetosheath. Two forces, the solar wind pressure force and Earth's magnetic force, compete each other at the boundary. Thus, the boundary called magnetopause is formed at the location where these forces balance each other. Magnetic reconnection may occur at this boundary if the magnetic field orientation is proper (see Section 2.3.1).

2.2.3. Magnetotail, Plasma Sheet and Auroral Oval: As deflected around the magnetosphere, solar wind stretches geomagnetic field lines out into a long, comet-like tail on the night side of the Earth which is called the magnetic tail or magnetotail. Geomagnetic field lines on the outer boundary of the magnetosphere may become connected to interplanetary magnetic field lines (IMF) that are rooted on the Sun. Thus, the magnetic tail is occupied with the field lines which one ends are in the solar wind and the other in the ionosphere (connected field lines). Plasma from the Sun thereby gains entry to the inner parts of the magnetosphere. The efficiency of this mechanism depends on the relative orientation of the interplanetary and geomagnetic field lines (section 2.3.1). Near the Earth, the ionospheric feet of these field lines are pulled from the dayside, across the polar cap, to the midnight regions within about two hours.

Plasma sheet is the central region of the magnetic tail in which the oppositely directed geomagnetic field lines take place. Some of these field lines can become connected in the center of the geomagnetic tail. Charged particles on these field lines are accelerated to a few thousand electron-volts. Electrons are ejected toward the Earth as the field line along the high latitude boundary of the plasma sheet becomes shorter. These electrons may be accelerated further by other physical processes at an altitude about one Earth radius (1 Re). They reach the Earth's upper atmosphere at a geomagnetic latitude near 67°. They collide with atmospheric molecules and atoms just above 80-100 km altitude and excite them into higher energy states. The excited atoms and molecules then fall back to their ground state, emitting blue, green or red line radiation that is characteristics of the gases at those heights. This way, aurorae are produced; one in the Earth's northern polar atmosphere and the other in the southern polar atmosphere as large rings of light, the center of each ring being near the geomagnetic pole.
Photons of energetic electromagnetic radiation (extreme ultraviolet and X-radiation) arrive at the Earth eight minutes after the energy, which is contained in the magnetic fields of the solar corona and associated with a sunspot group, is explosively released. These photons perturb the dayside ionosphere. Energetic solar protons are guided by the interplanetary magnetic field and geomagnetic field into the polar atmosphere some hours afterwards. The enhanced ionospheric plasma densities, which they produce, cause difficult radio propagation conditions at high latitudes. Two days or so later, a plasma shock wave often passes the Earth, enveloping it in a dense, hot and strongly magnetized plasma that compresses the magnetosphere. Auroral substorms, which are time-dependent phenomena, increase in frequency and intensity. Hot plasma is injected into the Earth’s magnetosphere to form an enhanced ring current which creates the geomagnetic field decrease that indicates the main phase of a magnetic storm. Because of increased distortion auroral ovals move to lower geomagnetic latitudes, creating a disturbed ionosphere there. Intense thermospheric wind systems, with winds of several hundred meters per second and sometimes of a world-wide scale, are generated during magnetic storms. There is considerable joule heating along the auroral oval (Figure 2.6). The energy input to the auroral oval is some tens of thousands of megawatts or more. Energy is carried away by, for example, gravity waves propagating to the lower latitudes.

The north and south polar-regions are windows to the geospace. Plasma instabilities and electric currents flowing up and down along the geomagnetic field lines. These currents are connected across the ionosphere via auroral electrojet. Hall currents measured in millions of amperes flow in the ionosphere whose conductivity has been enhanced by the precipitating energetic charged particles. The geomagnetic field observed at ground level below the auroral ionosphere is disturbed on timescales ranging from a minute to several hours.

2.2.4. Radiation Belts and Plasmasphere. Somewhat nearer the Earth, the energetic particles belts lie at the feet of geomagnetic field lines of slightly lower latitudes than auroral oval. These are the trapped radiation belts, the Van Allen Belts. The positively charged particles here constitute a westward flowing ring current (see Figure 2.10 in the next section) which slightly decreases the geomagnetic field strength on the Earth’s surface, especially near the equator. Radio waves traveling though radiation belts can cause energetic particle precipitation from this region into
the atmosphere. Even closer to the Earth, we see a region which consists of cold particles from the Earth’s atmosphere, the plasmasphere. The plasmasphere is corotating with the Earth. It is mapped down to Earth’s ionosphere as deep as the F-region heights (~ 200 kms) and affect the level of ionization and temperatures there.

2.2.5. Polar Cusp and Cleft: Other important feature of the magnetosphere is the cusp or cleft. The magnetospheric cusp is a narrow region, elongated in longitude and extending down from the high latitude magnetopause into the polar ionosphere. It is filled with plasma nearly identical in properties with the magnetosheath plasma, and therefore it is generally assumed to originate there. The two cusps (one in each hemisphere) are in effect extensions of interplanetary plasma down to Earth’s upper atmosphere. Cusps consist of magnetic field lines that extend directly into the magnetosheath. Then magnetosheath plasma enters the cusp by bulk flow parallel to the magnetic field. Compared to the polar cap field lines, cusp field lines are connected to the magnetosheath field lines on the dayside where the flow is subsonic just passed the bow shock whereas the polar cap field lines are connected to the magnetosheath far downstream of the magnetosheath where the flow again becomes subsonic. Only the subsonic plasma satisfies the necessary flow conditions for entry into the lower magnetosphere and eventually down into the ionosphere. Whatever the origin of the cusp, it allows a sizable amount of low energy (on the order of a few hundred eV) plasma precipitate into the ionosphere, which in turn produces significant heating effects in the ionosphere, particularly during the polar winter when the ionization source from Sun is absent. Observations also show that the O+ ions from the ionosphere escape through the polar cusp to the outer space.

2.3. Solar-Terrestrial Coupling Ways: Dynamics

Any physical process causing solar wind particles to enter into the Earth’s atmosphere or vice versa is considered as a way of transferring energy and momentum into or out of the atmospheric region. There are several hypotheses suggested for the coupling between the solar wind and Earth’s magnetosphere, which eventually lead into the deposition of the solar wind particles into the Earth’s upper atmosphere. We now review some of these processes in the literature.
2.3.1. Magnetic Reconnection versus Viscous Interaction: The Role of IMF orientations

The most important and effective way to store the solar wind particles into magnetosphere is the magnetic reconnection, which occurs at the magnetopause boundary in the presence of oppositely directed interplanetary magnetic field and geomagnetic field. It is proposed first by Dungey (1961). Magnetic connection opens the magnetospheric boundary into the solar wind and lets the solar wind particle and magnetic energy into the magnetosphere and from there to the upper atmosphere along the connected field lines. The magnetosphere in this stage is called open magnetosphere. Figure 2.7 gives this geometry. The open model predicts strong solar wind-magnetosphere interaction whenever the IMF has a southward component (with respect to the Earth) and this prediction has been verified by the satellite observations.

In the presence of the magnetic reconnection, another type of a less effective interaction is the aerodynamic viscous interaction along the magnetopause boundary between the solar wind flowing tailward and geoplasma. This type of interaction is expected when the geomagnetic field lines and IMF are parallel each other which occurs when IMF point northward at the magnetopause. In this case the magnetosphere is called closed magnetosphere. Figure 2.8 represents this case. Access of the particles along the field lines in this case is prohibited as a result of parallel directions of the field lines. Particle diffusion associated with the plasma instabilities and wave-particle interactions also occurs along the magnetopause boundary. Under these conditions, instabilities generate plasma waves and these waves scatter the particles onto the closed field lines.

2.3.2. Local Reconnection Events: Flux Transfer Events, Patchy, Sporadic Reconnection

Magnetic merging can happen in one of two ways: steady state reconnection and localized sporadic reconnection. Figure 2.7 depicts the steady state topology. This configuration allows solar wind particles to penetrate the magnetopause by simple guiding center motion along open magnetic field lines. In addition, the magnetosheath particles have direct access to the polar cleft along open field lines. In contrast, localized sporadic reconnection occurs only in a limited region for short
periods of time. Such localized merging can produce small plasma tubes (~1Re in size), which convect over the geomagnetic poles into the tail. Theories predict the tube-forming process twists the tube’s cylindrical shape. The magnetic “flux tubes” formed by this patchy reconnection process are sometimes called “flux transfer events (FTEs)” (Russell and Elphic, 1979). Observations show FTEs form during southward Bz, but are almost never observed during north conditions.

Regardless of the entry mechanism, most of the solar wind particles which cross the magnetopause convect back to, and become temporarily stored in the plasma sheet. Two oppositely directed tail lobe fields could come into contact (night side reconnection), and the resulting magnetic field annihilation can release about 5 keV worth of energy which will be transformed into plasma kinetic energy. This way particles in the plasma sheet can be accelerated and as a result moved very fast into the upper atmosphere along the field lines and form aurorae.

2.3.3. Magnetospheric Substorms

The level of magnetospheric activity varies widely. Variations in the solar wind produce time variations in the solar wind-magnetosphere interaction as the magnetosphere tries to adjust to a new state appropriate to the new solar wind often occur in the form of sharp discontinuities or shock waves. When these pressure discontinuities convect past the Earth, they often trigger large scale, world wide magnetospheric disturbances known as geomagnetic storms. The main phase of the geomagnetic storm lasts from several hours to several days during which worldwide surface magnetic field is generally depressed in magnitude because of impulsive injections of fresh plasma into the magnetospheric ring current (see Section 2.3.4).

This ring current enhancement is due to injected tail plasma in association with magnetospheric substorms. The short-lived substorm impulses are thought to be due to large scale instabilities in the magnetospheric tail. The magnetospheric tail is maintained by a current that flows from dawn toward dusk in the center of the plasma sheet (see Section 2.3.4). This current sheet is unstable to perturbations which allow magnetic merging to occur between 10-20 Re and the subsequent acceleration of magnetospheric tail plasma (see Figure 2.10). Observations indicate that the excess free energy stored in the magnetotail can approach 1016 Joules. Since a typical substorm takes about 40 minutes, a substorm can dissipate energy at a rate of about 5x10^{13} watts into the high latitude ionosphere.
Although there are several models on what drive the substorms, all of the models incorporates with an unloading of magnetic field energy via tail reconnection at the center of the plasma sheet. Substorms occur when the solar wind has a large magnetic field component pointing southward. A southward IMF causes enhanced merging of geomagnetic and interplanetary field lines at the dayside magnetopause, setting up a temporary net transfer of magnetic flux from the dayside magnetosphere into the tail region (see Figure 2.7). The process continues until the merging rate in the tail adjusts itself to match the increased connection rate at the dayside magnetopause, so that the tail flux does not increase indefinitely. Energy is stored in the increasing tail field for about one hour or more before an instability occurs resulting in substorm onset. The substorm deceases when the reservoir of available magnetic energy in the tail is depleted, but a new substorm cycle can then start if the solar wind field remains southerly directed.

Figure 2.9 shows a substorm example, relation to the southward directed IMF, and the energy deposited into the magnetosphere. The energy is calculated by $-V \cdot B_s$ where $V$ is the solar wind velocity and $B_s$ is correlated with the magnitude of the southward component of IMF. During the event, IMP-8 spacecraft was outside the bow shock measuring the solar wind parameters. Two scales on the right of the picture give the magnitude of $-V \cdot B_z$, where $B_z$ is southward component of IMF, and the total available solar wind energy input ($W_{\text{in}}$) is measured in units computed using a model of ionospheric currents derived from the ground magnetogram measurements. In the figure, an increase in the joule heating between 10:20 and 11:00 UT immediately with the increase in $-V \cdot B_z$. Observations show that after 11:00 UT intense auroral activity began, and the ionospheric current model generated a subsequent large increase in the joule heating rate which seems to favor the growth phase model.

The principal substorm signature on the Earth is the spectacular atmospheric auroral displays over the polar latitudes. In addition, the horizontal component of the surface geomagnetic field decreases at the latitudes where the aurora forms due to an ionospheric "electroject" current of about $10^6$ amps. Also, Pi-2 (see Section 2.3.4) waves caused by the rapid changes in plasma flow in the magnetosphere are observed on the ground.
2.3.4. Magnetospheric Currents

The shape of the magnetosphere (compressed dayside and magnetotail geometry) is preserved and maintained by several current systems supplied during the solar wind plasma and geomagnetic field lines. The effects of these current systems are superposed to create the magnetosphere. Figure 2.10 gives a sketch of the current systems observed as a result of solar wind and geomagnetic field interaction. These current systems are:

1. Magnetopause current system
2. Cross-tail current system
3. Ring current system
4. Field-aligned current system

In addition to these, there are other types of current flowing in the ionosphere and the closure of these magnetospheric currents. All of these currents contribute to the overall geomagnetic configuration. However, among these it is the field-aligned currents which flow along the geomagnetic field lines and carry information between solar wind, magnetosphere, and ionosphere. These currents vary with the geomagnetic activity because the field lines along which the currents flow map into the magnetotail. The total current fed into and out of the ionosphere by these currents ranges from 1 to 3 amps (typical current density is about 10-6 amp/m²).

Field-aligned currents show a two-component structure. Figure 2.11 shows areas of downward field-aligned currents (shaded) and upward currents (unshaded). The field-aligned currents in the poleward portion of the auroral oval are called Region 1 currents and the equatorward portion of the field-aligned currents are called the Region 2 currents. Therefore, in the evening sector Region 2 field-aligned currents flow into the ionosphere and Region 1 field-aligned currents flow out of the ionosphere. It is the reverse on the morning side.

2.3.5. Magnetospheric Waves

Magnetohydrodynamic and electromagnetic waves generated in the magnetosphere can propagate along the ambient magnetic field direction and can be detected by ground-based instruments. For example, micropulsations (waves in the frequency range ~ 0.001 Hz to ~ 1 Hz) were first detected on the ground. This is seen in the top panel of Figure 2.12. Micropulsations are observed during both quiet and
disturbed geomagnetic conditions and they have amplitudes of a few \(10^3\) nT to several 10 nT. Some are very periodic called continuous pulsations, Pc, (Figure 2.12, bottom panel) while others are irregular called irregular pulsations, Pi (Figure 2.12, top panel). Continuous pulsations or Pc pulsations are seen in quasi-sinusoidal form with well-defined spectral peak. They are broken into subgroups on the basis of their periods starting with Pc-1 in the 0.2-5 Hz band ending with Pc-5 in the 1.7-6.7 mHz band. The names assigned to different frequency bands are given in Table 2.1. In Figure 2.13, typical magnetic pulsation signatures are illustrated, which includes both ground-based observations (bottom panel) from a chain of ground stations at different latitudes and simultaneous measurements from a spacecraft, ISEE-2, (top panel) in the near-equatorial magnetosphere.

Dungey was the first who suggested that magnetohydrodynamic waves in the outer atmosphere were the sources of oscillating or pulsating magnetic field observed on the surface (Kivelson and Russell, 1995). In particular, the distinct periods of Pc pulsations suggested a resonant process, and Dungey proposed that the pulsations were caused by waves standing along magnetic field lines and reflected at the ionospheres at the two ends. His idea later had been supported by both ground-based and spacecraft data.

2.4. Purpose and Relevance of This Study to the Solar Wind-Magnetosphere-Ionosphere-Upper Atmosphere Coupling

The solar wind interacts with the magnetosphere and ionosphere in several ways. This interaction starts at the bow shock. The solar wind and interplanetary magnetic field are first modified here. Then, the modified solar wind continues its way by flowing around the geomagnetic field within the magnetosheath. This study investigates how the solar wind can be modified by the energetic particles when they are present in the magnetosheath. The energetic particles were found to create cavities in which the solar wind characteristics are quite different than the surrounding solar wind (Sibeck, 1990; Sibeck, 2001). These cavities in turn change the local magnetopause boundary location.

The magnetopause is located at the place where the solar wind flow pressure is balanced by the geomagnetic field pressure. Any perturbation on the location of the magnetopause is transmitted to the underlying ionosphere and upper atmosphere through the field lines by both currents and waves. Figure 2.12 illustrates the
magnetopause and bow shock location in response to the high and low solar wind pressure. In Figure 2.14a, a larger magnetopause and wider magnetosheath is seen corresponding to the lower pressure in the solar wind while a smaller magnetopause and narrower magnetosheath is seen in Figure 2.14b corresponding to the higher solar wind pressure. In Figure 2.14b, it is also seen that the magnetic field line that intercepts the magnetopause is mapped to lower latitude on the Earth’s surface. By affecting the solar wind pressure, energetic particles are found to cause boundary motions which are in turn mapped onto the Earth’s ionosphere (Sibeck, 1991). The high altitude atmosphere is coupled with the ionosphere due to ion-neutral collisions. Therefore, the electrodynamics of the ionosphere further helps shape and modify the neutral atmosphere and conversely high altitude neutral wind dynamics can play a significant role in determining ionospheric structure.
3. MAGNETOSHEATH. ENERGETIC PARTICLES AND THEIR EFFECTS IN THE SOLAR WIND

3.1. Magnetosheath as determined by the Gas Dynamic Model

The magnetosheath has been investigated in detail by the gas dynamic model. The magnetosheath flow around the magnetospheric body is well represented by this aerodynamic model of the magnetosphere. Since the gas dynamic model ignores the magnetic field effects on the plasma, it fails in the magnetosheath where these effects become important especially at the magnetopause boundary (Kaymaz, 1996). In the gas dynamic model, the flow equations are solved without including magnetic field. Magnetic field is computed after the flow field has been determined. Here, we give gas dynamic model results in order to get some idea on the large scale characteristics of the flow and magnetic field within the magnetosheath.

In Figure 2.1, the velocity streamlines (a) and contours (b), density (c) and temperature (d) contours, and magnetic field (components perpendicular (e) and parallel (f) to the flow) contours are given for sonic mach number equal to 8 (Stahara et al. 1979). Magnetosheath parameters are given normalized to their corresponding solar wind values. Figures show that from the bow shock to the magnetopause boundary, density increases while the velocity decreases with respect to their solar wind values. Temperature is seen to increase as well. It increases by a factor of 20 in the subsolar magnetosheath. Magnetic field perpendicular to the flow increases from the bow shock to the magnetopause along the subsolar line while the parallel component decreases. Flow streamlines in panel (a) show that the shocked solar plasma flow around the magnetospheric obstacle like a water flow around a rock in the river.

3.2. On the Possible Source of Energetic Particles

Magnetosheath consists of shocked solar wind plasma as well as which has escaped from the magnetosphere. The magnetosheath, therefore, is an important region since it contains information about both the processes occurring at the bow shock and the energetic particle populations within the magnetosphere.

Williams et al. (1988) studied three-dimensional measurements of magnetosheath ions at energies between 200 eV and 2 MeV and found that the ions
consisted of at least two distinguishable components: a shocked solar wind component at energies below about 5 keV and magnetospheric component above about 5keV. Sibeck et al. (1987) investigated the expected leakage of magnetospheric particles into the magnetosheath due to the intersection of the outer drift paths of magnetospheric particles with the magnetopause. This leakage model predicts that magnetospheric ions and electrons should continuously be lost into the magnetosheath.

We can categorize the energetic particle sources mainly into two groups; one being the upstream region of the Earth’s bow shock and the other is being the Earth’s magnetosphere, specifically the plasma sheet. Recently, Earth’s polar cusps have also been suggested as a source for the energetic particles in the magnetosheath (Chen et al., 1998). However, this is currently one of the controversial issues on this topic.

In this study, we do not discuss the origin of the energetic particles in the magnetosheath. However, as the energetic particles in the solar wind, which is a part of our survey in this work, are due foreshock, we give a summary on the foreshock below. Also disturbances produced in the foreshock are naturally expected to be convected into the magnetosheath where in turn have an effect on the magnetopause boundary motion.

3.3. Foreshock

The region upstream from the Earth’s bow shock is natural plasma laboratory which contains a variety of wave and particle phenomena. The most outstanding characteristic of this region is the presence of a spatially asymmetric region of backstreaming ions and electrons, as well as electrostatic and electromagnetic waves on the magnetic field lines connected to the bow shock. This region is called the “foreshock”. The asymmetry of this region is associated with the curved bow shock and the orientation of the interplanetary magnetic field. The particles are accelerated via several possible mechanisms and provide a source of free energy for various plasma instabilities as they move upstream in the incoming solar wind flow. Waves can arise due to various instabilities. The waves in turn later alter the distribution of the backstreaming particles. Furthermore, the interaction between large amplitude upstream waves and planetary bow shock can modify the structure of the bow shock. The downstream convection of these waves along the solar wind streamlines will
cause a more turbulent magnetosheath. The oscillations in response to the pressure fluctuations associated with these waves will couple into the magnetosphere and become responsible for some of the dayside magnetic pulsations in the magnetosphere. Thus upstream waves affect the entire solar wind interaction with the Earth from causing changes in the solar wind itself to affecting the nature of waves seen on the surface of the Earth (Le, 1991).

Studying the upstream phenomena in the foreshock region is important for several reasons. First of all, this is a natural plasma laboratory for all sorts of wave phenomena and wave-particle, wave-wave interaction which can't be produced in the laboratory experiments. Secondly, the energy flux of particles moving upstream is estimated to be $10^{10}$-$10^{11}$ Joule/s, comparable to a modest magnetospheric substorm (Sentman et al., 1981). The supersonic solar wind continually carries the waves generated in front of the bow shock downstream, and the wave transmission and energy transfer have significant impacts on the Earth's bow shock and magnetosphere.

Figure 3.1 from Le (1991) shows schematically the foreshock phenomena when the interplanetary magnetic field is oriented near the average spiral angle near 1 AU (also Russell and Hoppe, 1983). The upper panel shows the ion foreshock and the lower panel shows the ULF wave foreshock. This picture is based on previous observations and describes qualitatively several subregions of the Earth's foreshock. The physical processes in this region can be summarized as follows. When the supersonic solar wind flow comes to the Earth from the Sun, the Earth's magnetosphere acts as an obstacle to the flow. As a result, the bow shock forms in front of the magnetopause and the region between contains the shocked plasma, which has become subsonic after the shock transition. At the bow shock, a very small fraction of solar wind particles fails to cross the shock transition, and is reflected with sufficient velocity to propagate back in to the solar wind via various reflection and acceleration mechanisms. There are also a small number of energetic magnetosheath particles which can leak into the upstream region. The interaction of backstreaming particles with the incoming solar wind flow will cause a wide variety of waves. The region containing these particles and waves is called the foreshock.

As soon as the charged particles leave the bow shock due to reflection or leakage, they move in the ambient interplanetary magnetic and electric fields. Their motion is guided by the magnetic field and they also drift perpendicular to this field.
due to the interplanetary electric field. The foreshock is the region which is magnetically connected to the bow shock. However, not all connected field lines contain electrons and/or ions. For the usual Parker spiral IMF there is a spatial symmetry in the foreshock. In this configuration, if particles flowed back along the field line at an infinite velocity, the outer boundary of the foreshock would be the tangent IMF field line.

The foreshock consists of several sub-regions. If the interplanetary magnetic field makes a finite angle to the solar wind flow, which is the usual case, the field lines are convected downstream by the solar wind flow. When the backstreaming particles are propagating along the interplanetary magnetic fields, they are subject to the solar wind convection electric field. The downstream $\mathbf{E} \times \mathbf{B}$ drift and the different source region and velocity of electrons and ions separate the electron foreshock from the ion foreshock. The backstreaming electrons have a much greater velocity than that of the ions along the magnetic field lines if they have comparable energies. But they have the same $\mathbf{E} \times \mathbf{B}$ drift velocity where $\mathbf{E}$ and $\mathbf{B}$ are the electric field and magnetic field vectors respectively. As a result, the ion foreshock is further downstream from the electron foreshock, as seen in Figure 3.1. Both ion and electron foreshock also have several sub-regions because the particles may be divided into several groups with different energy or angular distribution.

The propagation of backstreaming particles relative to the solar wind is unstable and will generate a variety of upstream waves over a wide frequency range. In general, the foreshock of each type of wave is superposed on the foreshock of the particles group, which is the source of free energy. Many types of instabilities associated with these wave and particles have been identified including VLF waves (mainly ion acoustic waves, whistler waves) and ULF waves (MHD waves, discrete wave packets, ion cyclotron waves).

Ions that have been either reflected at the shock or leaked from the magnetosheath stream into the solar wind along the magnetic field; their presence defines the ion foreshock (Thomsen, 1985). Since ions with energies comparable to the electrons have much lower speed than the electrons, ions will convect a greater distance traveled along the field. For this reason, the upstream edge of the ion foreshock is located some distance downstream from the electron foreshock edge.

The backstreaming ions provide the free energy for a variety of modes, both electrostatic and electromagnetic. The most prominent waves associated with the
backstreaming ions are lower frequency electromagnetic waves and electrostatic ion acoustic waves.

The ions that populate the ion foreshock originate from a wide region, including quasi-parallel and quasi-perpendicular parts of the bow shock. The upstream electromagnetic waves, which are driven by the backstreaming ions, grow to large amplitudes and can produce a substantial slowing and heating of the solar wind. These waves convect with the solar wind flow and eventually encounter the quasi-parallel part of the bow shock. There exist a dynamical interplay between ion foreshock and the quasi-parallel shock whereby the backstreaming ions modify the upstream region through the generation of large amplitude waves which then flow back into and modify the shock. Moreover, various large-amplitude upstream perturbations convect through the magnetosheath and impinge on the magnetopause. The disturbances caused by these upstream perturbations are detectable deep within the Earth’s magnetosphere (Fairfield et al., 1990).

The amplitude of low frequency waves excited in the ion foreshock was found to increase with increasing depth in the foreshock and their frequency spectrum is found to be very broad (0.003 Hz < f < 0.5 Hz) (Russell et al., 1987). It has been suggested that if Pc 3-4 waves observed in the magnetosphere are transmitted from the foreshock through bow shock and magnetosheath, there must be a significant filtering somewhere between the ion foreshock and the inner magnetosphere. ULF waves were investigated very broadly by Le and Russell (1990a). They have shown that these waves are large scale features, with typical transverse scale lengths on the order of wavelength of the waves (~1 Re). These waves might then be expected to induce similar scale-size variations in the Earth’s bow shock.

In addition to ULF waves, discrete very large amplitude, shock-like fluctuations are often observed in the ion foreshock. These are called ‘pulsations’ (Greenstad et al., 1970) and shocklets (Hoppe et al., 1981). It has been experimentally shown that pulsations are actually the brief encounters of bow shock while the shocklets are upstream origin and convecting over spacecraft. Presence of both events presents the strongly nonlinear wave evolution in the ion foreshock region (Onsager and Thomsen, 1991).

Besides the shocklets and pulsations, a number of more extreme disturbances have been observed near the Earth’s bow shock, primarily upstream from the quasi-
parallel shock but also in the magnetosheath. These disturbances are usually localized regions characterized by plasma with temperatures an order of magnitude or more above the ambient solar wind temperature, and with bulk flow that is strongly deflected relative to the surrounding plasma. Several names were given these plasma regions, including "active current sheets", "hot diamagnetic cavities", "three dimensional plasma structures with anomalous flow directions", "hot deflected flow regimes", and "hot flow anomalies" (Onsager and Thomsen, 1991).

As we will see in detail in Sections 3.3 and 3.4, in these events, typically there is a high density, high-magnetic field, shock-like compression region on one or both of the event boundaries, while density within the hot, internal region is often near or below the ambient solar wind density. The plasma is slowed and deflected within the event, sometimes by more than 90°. (i.e. plasma bulk velocity has a component in the sunward direction). The outer edges of the event boundaries have been shown in many cases to be quasi-perpendicular, fast mode shocks (Fuselier et al., 1987), whereas the inner edges of the event boundaries (separating the shocked, compressed plasma from the hot, lower density internal region) appear to be tangential discontinuities. The direction of the flow is always in the same direction as flow around the Earth’s magnetosphere, i.e. dawnward on the dawn side of local noon and duskward on the dusk side. This ordering of the flow with respect to local noon indicates that these structures must be influenced by bow shock or magnetosphere in some way.

A number of mechanisms have been proposed to explain the formation of HFAs, including magnetic reconnection at the magnetopause and the amplification of rotational discontinuities as they convect through the bow shock and magnetosheath the interaction of the current sheets in the solar wind with the bow shock, and coupling of ions reflected off the Earth’s bow shock to the solar wind plasma (Onsager and Thomsen, 1991).

3.4. Pressure Variations and Their Effects on the Magnetosphere

The most fundamental mode of interaction between solar wind and the Earth’s magnetosphere can be described as a compression of the Earth’s dipole magnetic field by the external solar wind plasma until pressure balance is achieved between the internal magnetosphere field and the exterior solar wind plasma. Changes in the solar wind pressure determine the level interaction between the solar
wind and Earth’s magnetosphere. The magnetopause boundary moves back and forth, or from/toward the Earth, and the inflation/deflation of the internal magnetic field at the magnetopause occur as response to the solar wind pressure variation. Therefore, it is important to determine the reasons behind pressure variations in the solar wind.

Solar wind pressure changes can be grouped into two categories. One is the changes inherent to the solar wind, i.e. global changes resulted from the changes occurring within the Sun, or large-scale interplanetary shocks occurring along the way of the solar wind to the Earth. These changes are spatially more effective and cause a global motion of the magnetopause while also temporarily longer. The other changes are caused by the upstream waves within the foreshock and more temporal and spatially restricted to where and when the foreshock events occur. Another group of phenomena is found called as ‘hot deflected flow regions’ or ‘other names’ and these are structures within the foreshock and can be counted as part of foreshock. The foreshock related changes depend on the IMF direction as the absence or presence, or the spatial extend of the region.

By studying AMPTE CCE, GOES 5 and GOES 6 spacecraft, Fairfield et al. (1990) observed magnetic field enhancements and depressions on the time scales of minutes which are also seen in the pressure variations in the solar wind. Figure 3.2 from his paper shows these relations between magnetic field, density and pressure variations. All the parameters are seen to show the similar variations in this figure. Enhanced kinetic pressure ($P_{kin}$=nkT) in the upstream solar wind corresponds to compressions of the magnetic field in the subsolar equatorial magnetosphere. Fairfield further showed that these pressure enhancements occur within or adjacent to the foreshock and due largely to density enhancements. Since the density and magnetic field in the undisturbed solar wind is anti-correlated, he concluded that these events are not inherent in the solar wind but rather are the result of the solar wind/foreshock/bow shock interaction. Figure 3.3 shows an example of the upstream waves giving an excellent correlation between the density and magnetic field variations. Fairfield’s findings imply a mode of interaction between the solar wind and the magnetosphere whereby the density changes produced in the foreshock subsequently convect through the bow shock and impinge on the magnetosphere. These upstream pressure perturbations should create significant effects on the
magnetopause and at the foot of nearby field lines that lead to the polar cusp ionosphere.

Fairfield et al. (1990) further pointed out that since the foreshock has been observed frequently on the dawn quadrant due to the spiral nature of the IMF, pressure variations on this quadrant occur more frequently and as a result spacecraft traveling through this region record more frequent crossing of magnetopause which indeed the case in Wrenn et al. (1981), Rufenach et al. (1989), Howe and Siscoe (1972).

One of the other important features driven from Fairfield’s study (1990) is related to the solar wind velocity. Sometimes, he sees large decreases in the solar wind velocity on the order of 100 km/sec within the foreshock. Such decreases in his study are found to be associated with decreases in magnetospheric field strengths and densities. Figure 3.4 is an example of this type. These events are called ‘hot deflected flow’ events, which later named in the literature as Hot Flow Anomalies (HFAs). Existence of an extended foreshock seem to be the cause the flow of the solar wind around the magnetosphere and decrease the solar wind pressure on the subsolar magnetosphere. When IMF eliminates the foreshock in the subsolar region, the subsolar magnetosphere may absorb the full impact of the solar wind and magnetosphere may be more compressed than if there were an upstream foreshock. Appearance or presence of localized region of these hot deflected flow regions near the bow shock also result in the compression of the magnetosphere.

From the energetic particles point of view, these phenomena are important in modulating the total solar wind energy flux. Upstream modulation of solar wind flux can have a significant effect on the magnetosphere since energies involved are large compared to the few percent of the incident solar wind energy that is extracted by the magnetosphere. Fairfield et al’s study (1990) concludes that although many people are working on the effects of the pressure variations inherent in the undisturbed solar wind, these bow shock associated variations seem to be of equal or even greater importance.

Even though the pressure changes in the upstream region appears to be the foreshock/bow shock related, the mechanisms that produces these changes are not still complete. Many of the pressure change events seem to be related to the changes in IMF direction. This implies that even in the presence of a solar wind that is steady
in velocity and density, but which carries an imbedded interplanetary magnetic field orientation, there will be variation in the pressure exerted on the magnetopause.

Russell et al. (1997) studied the effect of foreshock on the motion of the dayside magnetopause for the purpose of revealing the role of IMF direction and pressure variations in moving the boundary. They find that the pressure fluctuations could directly move the boundary and also enhance the reconnection rate when the IMF was southward temporarily leading to erosion of the magnetopause and causing magnetopause oscillations. In addition, magnetic waves themselves could lead to periodically enhanced reconnection and oscillations of the boundary. They conclude that both the foreshock and direction of IMF through flux transfer events play a role in causing the magnetopause to oscillate.

Magnetopause boundary motion resulted from variations in the solar wind pressure has been investigated in detail by Sibeck (1990). Impulsive variation in the solar wind dynamic pressure drive magnetopause motion, magnetospheric magnetic field compressions, transient oscillations in high latitude ionospheric flows, ground magnetic field pulsations, and increased ELF/VLF wave activity. He suggested a qualitative model for the effects of solar wind/magnetosheath dynamic pressure variations on the magnetosphere, including magnetopause, magnetospheric, and ground signatures. As seen in Figure 3.5, His model given in Figure 3.5 explains most of his experimental data in the solar wind, magnetosheath and on the ground. High pressures cause the magnetopause boundary move in while low pressures out. As a result, these pressure variations or pulses generate moving disturbances on the boundary. The magnetopause will move radially in and out while adjusting itself to the pressure variations. The amplitude of the wavy magnetopause motion depends on the variation in the solar wind dynamic pressure, which increases by a factor of 2 to 3 across typical interplanetary shocks (Siscoe et al., 1968) and the bow shock produced pressure pulses reported by Sibeck (1990). The balance between solar wind dynamic and magnetospheric magnetic pressures indicates that the distance from Earth to the magnetopause is proportional to the sixth root of the dynamic pressure. Thus typical dynamic pressure variations cause the magnetopause position to vary by a factor of 1 to 2. Since subsolar magnetopause location is generally near 10 Re, this gives an upper limit of about 2 Re on the magnetopause motion induced by shocks and pressure pulses (Sibeck, 1990) and Sibeck and Croley (1991).
The north-south IMF direction also controls the amplitude of the magnetopause motion (Russell et al., 1997). While impulsive increases in solar wind dynamic pressure are equally likely for northward and southward IMF, the magnetospheric response to these increases depends on the IMF orientation. When IMF is southward, the low latitude boundary layer (LLBL) is generally thin and perhaps no more gradients in plasma parameters. Conversely when the IMF is northward LLBL is thicker and forms a region of more uniform (dense, cold) plasma within the magnetopause. However there is no dependence of pressure pulse occurrences on the IMF. Every pressure pulse should compress the magnetopause (Sibeck and Croley, 1991).

Figures 3.6 and 3.7 give a view and the characteristics of the magnetospheric regions during the passage of a pressure disturbance carried by a interplanetary discontinuity. Figure 3.8 presents the expected magnetic field, plasma and energetic particle signature which a spacecraft (point A in Figures 3.5 and 3.7) in the magnetosphere observes during brief crossing into the magnetosheath caused by pressure. Figure 3.9 illustrates how these perturbations couple to the high latitudes of the Earth’s atmosphere.

Figure 3.10 gives a time series example of magnetopause crossing caused by the pressure variations in the magnetosheath. Magnetospheric layers are shown across the top panel. Figure shows while the plasma pressure increases the magnetic pressure decreases owing to the decrease in the magnetic field strength. Increasing plasma pressure compresses the magnetopause and leaves the spacecraft in the magnetosheath. However, total pressure stays constant during the event. This figure is an example how pressure variations move the boundary inward and outward.

Figure 3.11 shows another example from 10:43 to 10:59 on day October 28, 1984. The magnetospheric layers on the top of the figure correspond to the ones in Figure 3.8. Figure 3.12 gives the plasma observations corresponding to Figure 3.11. An enhanced density and depressed temperature mark this event. Energetic particles drop to background levels in this example. Figure 3.13 shows the thermal, magnetic, and total pressures for the same event. The thermal pressure fell to low values in region 3 but maximizes in regions 2 and 4. The magnetic field strength maximizes in region 3 as well. Total pressure is seen to peak at the center of this event. Figure gives a brief encounter of the magnetopause boundary. Figures 3.11-3 13 indicate the presence of cold, dense plasma in region 3 which is recognized as the depletion layer.
just outside the magnetopause. Region 4 denotes the magnetosheath and plasma there is colder, faster, and denser than that in region 3. However, magnetosheath characteristics can be different depending on where in the magnetosheath. In other words, characteristics of magnetosheath closer to the boundary are predicted and observed different than those further in the magnetosheath (Stahara et al., 1979; Spreiter et al., 1981). Further in the magnetosheath lower velocities and densities are observed. Transition from low total pressure in the magnetosphere to high total pressure in the magnetosheath shows that the magnetosheath pressure pushed the magnetopause inward so that the spacecraft stayed in the magnetosheath.

Recent observations from Interball spacecraft also reveal detail characteristics of magnetopause motion with the higher resolution data. Safrankova et al. (1998), using Interball observations, observed small scale characteristics of the magnetopause motion. Figure 3.14 from their paper shows multiple crossings of the magnetopause boundary. To explain these back and forth motion of the boundary, they invoke with the Sibeck's model of boundary motion as result of an increased plasma pressure in the magnetosheath. Several brief encounters of magnetopause boundary and magnetosheath in their events are explained by the deformation of the magnetopause surface which moves with the velocity of the magnetosheath plasma. Figure 3.15 gives their schematic for Interball boundary encounters. They estimated the spatial characteristics of these events as $10^3$ km. They found magnetosheath-like plasma pulses have about ~30 seconds duration which is equal 7500 km of spatial extentenon along the x-direction and in the y-direction on the order of 1000 km. The amplitude of waves can also be predicted as a few thousand kilometers.

3.5. Effects of High Energetic Particles on the Upstream Solar Wind Plasma and Magnetic Field

Previous section summarized the boundary motion caused by the pressure variations in the magnetosheath and in the solar wind. This section presents results from the earlier studies on the transient events due high energetic particles.

The earliest study on the determination of the magnetosheath characteristics goes back to 1973. Using Heos 1 spacecraft data, Formisano et al. (1973) classified the magnetosheath in different stages depending on the presence of the upstream waves in front of the bow shock. They found that when the upstream waves are
present, the magnetosheath densities are lower and these are associated with high thermal speeds. Figures 3.16 and 3.17 show their results. Formisano et al. (1973) carried out their study during a time when there were not enough spacecraft data and resolution of the data for these early studies were very low.

It is now well established that the foreshock causes pressure pulses and these pressure pulses compress magnetopause. However the IMF direction within the foreshock is a very important factor in driving the magnetopause in motion. The IMF is constantly changing disconnecting the spacecraft just upstream from the bow shock to that boundary. A fraction of solar wind ions incident on the bow shock are energized and reflected back into the solar wind along the magnetic field lines connected to the bow shock. Although their number density is small, suprathermal ions contribute substantially to the thermal pressures in the region connected to the bow shock. The enhanced pressures cause the bundle of connected magnetic field lines to expand outward into the surrounding solar wind plasma. Densities and magnetic field strengths decrease diamagnetically within the expanding bundle, but increase just outside the bundle in the region compressed magnetic field lines unconnected to the bow shock. This is supported by kinetic simulations of Thomas and Brecht (1988). Figure 3.18 presents their model output in which the density and magnetic field decreases at the core of the energetic particle beam surrounded by two enhanced density and magnetic field.

Figure 3.19 from Sibeck et al. (1999) gives a model of plasma, magnetic field and energetic particles during the passage of boundary waves driven by pressure variations produced in the foreshock. It illustrates the formation of a foreshock cavity and its subsequent interaction with the magnetosphere. In Figure 3.19a, a narrow slab of sunward and northward magnetic field lines first encounters the southern bow shock. Prior to the arrival of slab, the IMF points dawnward. After the passage of the slab, the IMF points duskward. Consequently, the only upstream field lines in the noon-midnight meridional plane connected to the bow shock are those within the slab itself. As these magnetic field lines first encounter the bow shock, ions energized and reflected to stream back upstream into the solar wind. The ions depress IMF strengths and densities within the slab creating a diamagnetic cavity (light shading). The expanding cavity compresses and enhances IMF strengths and densities just outside the leading edge of the slab (dark shading).
As seen in Figure 3.19b, the solar wind sweeps the slab and foreshock cavity anti-sunward. Both the intersection of the slab with the bow shock and the foreshock cavity move northward. Ions continue to be reflected from the bow shock and scattered within the slab, creating a growing diamagnetic cavity that further compresses surrounding regions both ahead of and behind the slab. Finally, those portions of the cavity that were upstream from the southern bow shock now lie downstream of that boundary: density increases and decreases associated with the cavity have been transmitted as pressure variations into the magnetosheath.

Figure 3.19c depicts the subsequent evolution of the cavity and its interaction with the magnetopause. The magnetosheath flow continues to sweep the growing foreshock cavity northward and trailing pressure enhancements bounding the cavity through the magnetosheath: around the dawn and dusk flanks and over the northern magnetopause. The pressure increases compress the magnetopause inward, whereas the decrease within the cavity allows it to expand outward. As there was no significant cavity upstream from most of the southern bow shock, there is little or no response on the southern magnetopause.

If the spacecraft is located in the vicinity of magnetopause in the magnetosheath during the passage of the cavity, it will observe the cavities as regions of depressed densities and magnetic field strengths, but enhanced suprathermal particle fluxes, bounded by regions of enhanced densities and magnetic field strengths. However, the spacecraft may not remain within the magnetosheath. The depressed magnetosheath densities and pressures within the cavities permit the magnetopause to move outward past the observing spacecraft, which must then observe density increases bounding an interval of magnetospheric magnetic fields. Spacecraft located in the outer magnetosphere should exit into the magnetosheath on both sides of a region of rarefied magnetospheric magnetic field strengths. Finally, spacecraft that remain within the magnetosphere should observe transient magnetic field strength increases bounding a region of depressed magnetic field strengths.

Sibeck et al. (2001) studied Wind and IMP 8 plasma, magnetic field and energetic ion observations within the Earth's foreshock to determine the effects of energetic ion bursts on the ambient solar wind for comparison with model predictions. They found pressures associated with energetic ions depress foreshock magnetic field strengths and plasma densities. Figure 3.20 shows a time series example from their paper while Figure 3.21 gives scatter diagrams of magnetic field.
density and velocity for both IMP 8 and Wind for the example in Figure 3.20. It is clear that signatures on IMP 8, which was in the foreshock at the time of the observation, shows the expected trends while Wind parameters in the solar wind do not show any dependence. The magnitude of the depression is proportional to the intensity of energetic ions. This is given in Figure 3.22 for the interval from 12:00 to 16:00 in Figure 3.20. The depressed plasma and magnetic field sometimes pile up in narrow regions of enhanced plasma densities and magnetic field strengths, but depressed flow velocities at IMP 8 far upstream from the bow shock are less (20 % and 10 % respectively) than those seen in the events observed just outside the bow shock. The cavities occur preferentially during high speed solar wind streams but show no clear dependence on other solar wind parameters.

These findings together with the simulation results of Thomas and Brecht (1988) for the foreshock show that the bursts of energetic ions thermalize to create cavities of depressed densities, temperatures and magnetic field strengths, but enhanced total pressures (when the contribution of energetic ions to the total pressure is taken into account). The solar wind sweeps the cavities anti-sunward. As they expand, the cavities slow and compress the oncoming solar wind to form boundary regions of enhanced magnetic field strengths and densities.

Figure 3.23 is a schematic given by Sibeck (2001) and overlayed on the events in which the IMP 8 observed energetic ions in the foreshock to explain the observations. A bundle of toward sector IMF lines (arrows) lies imbedded within a region of northward pointing IMF lines (circles). Backstreaming ions thermalize within the bundle in the immediate vicinity of the bow shock, forming a heated cavity filled with suprathermal and energetic ions (light shading). Magnetic field strengths diminish within the cavity owing to diamagnetic effects. Enhanced pressures within the cavity cause it to expand outward into surrounding region, thereby compressing the nearby magnetic fields and densities (dark shading). The cavity poses an obstacle to the oncoming solar wind that should allow the magnetopause to expand outward.

Sibeck et al. (2001) also discusses the differences between these events and hot anomalies found in the previous studies. HFAs occur just outside the bow shock for the solar wind velocities greater than average solar wind velocities. They exhibit stronger (factor of 2 to 5) magnetic field and density enhancements bounding regions
of tenuous plasma, energetic electrons, decelerated and greatly deflected flows and weak magnetic field strengths.

Figure 3.23 also shows that owing to the spiral IMF orientation, the events are far more common upstream from the prenoon than postnoon shock. In their study, the common duration is found to be between 1-9 min but occasionally events lasting 100 min also were observed.

These previous studies give the signatures of plasma, magnetic field and energetic particles in the solar wind. The Sibeck’s model illustrates most of the observational signatures of the parameters in the upstream solar wind. However, it has not been observationally shown that how these energetic particles affect the plasma and magnetic environment in the magnetosheath and if the model also valid in the magnetosheath. Do we see the similar events in the magnetosheath? How do energetic particle modify the magnetosheath field and plasma characteristics? Are these related to the upstream variations in the foreshock? How are they connected to the IMF direction? We need a similar kind of case and statistical studies when the spacecraft in the magnetosheath in the presence of energetic in order to be able to answer these questions. This thesis is based on a survey study. It focuses on one of these open questions and addresses how energetic particles modify the magnetosheath environment.
4. SURVEY OF HIGH ENERGY PARTICLES IN THE MAGNETOSHEATH AND THEIR EFFECTS ON THE MAGNETOSHEATH FIELD AND PLASMA

4.1. Data Sets and Instruments

In order to study the effects of energetic particles on the magnetosheath environment, we survey the measurements of magnetic field (MFI), density (CORALL), velocity (CORALL), temperature (CORALL), energetic proton flux (DOK), and ion flux (VDP) measurements from Interball-1 spacecraft.

The Interball spacecraft was devoted to detailed studies of energy, momentum and mass transfer in the critical regions of the solar wind-magnetosphere system. It consists of two probes, Tail probe and Auroral probe. Tail probe is also called Interball-1 while Auroral probe is called Interball-2. Interball-1 was launched into a highly elliptical orbit with a period of 92 hours, and an inclination of 62.8° on August 3, 1995 (Zelenyi and Sauvaud, 1997). It has an apogee of 200 000 km. It is aimed to study the interactions of the solar wind with the magnetopause and the outer regions of the magnetosphere, i.e. the magnetosheath and tail. Specifically, processes in the geomagnetic tail, energization of particles upstream of the Earth’s bow shock, origin of particle population in the magnetosheath are some of the open questions which can be studied with Interball-1 probe. The Interball-1 spacecraft spins with a period of 2 min about an axis oriented to within 10° of the Earth-Sun line. To achieve this accuracy, the axis is reoriented each second orbit.

The Auroral probe was launched just after Tail probe to 65° inclination orbit, but with the apogee of 20 000 km above the northern auroral zone and polar cap. It is aimed to study the plasma sheet processes and mapping of the night side auroral oval to the central plasma sheet and physical processes in these regions. In our study, we use Interball-1, or Tail probe, for our magnetosheath survey. Figure 4.1 gives a schematic view of Interball-1 spacecraft (Kremenev et al., 1996).

Interball-1 carries several instruments. A list of instruments board on Interball-1 is given in Table 2 (Interball Kremenov et al, 1996). Figure 4.2 shows where the instruments are located on the spacecraft. For our purposes, we use plasma
detectors, magnetic field instruments, VDP instrument and energetic particle instrument shown in Figure 4.2. Omnidirectional Plasma Sensors (VDP) provide total flux measurements at the time resolutions ranging from 1 to 16 Hz. Each VDP plasma detector (Safrankova et al., 1997) measures the sum of the total ion flux and the electron flux detector with energies greater than 170 eV entering a wide-angle (±67°) Faraday Cup. In this study, we use 2-min averaged observations by Interball-1’s sunward-looking VDP detector taken with a 1 s resolution.

Interball-1 also carries the CORALL ion energy spectrometer (Yermolaev et al., 1997) and FM-3I magnetometer (Nozdrachev et al., 1998). CORALL measures ion distribution functions within the energy per charge range 30<E/q<24200 eV/q via 32 energy steps in five angular sectors covering a 5°×110° fan-shaped field of view. The centers of the sectors are oriented at look directions 42°, 66°, 90°, 114° and 138° relative to the Earth-Sun line. Densities, velocities, and temperatures can be calculated once each 120s spin period. Again in this study, we use 2 min averaged three component magnetic field observations by the FM-3I fluxgate magnetometer with a time resolution of 0.25 s.

DOK-2 energetic particle experiment (Lutsenko et al., 1998) on board Interball-1 has two pairs of detector. One detector of pair (1E, 2E) 0.3 mm thick has a foil absorbing protons with energies E<400 keV and measure in 20-400 keV range an electron spectrum. The second one (1P, 2P) 0.15 mm thick, supplied with a broom magnet, deflecting electrons up to 1500 keV (magnetic filter) measure spectrum of ions (protons) in 20-800 keV range. The exact value of threshold energy for each detector depends on its noise level and on thickness of dead layer of the detector (protons) and the foil (for electrons). It is determined by physical calibrations. Full aperture angles and geometric factors of electron and proton detectors are of 27°, 12.7°, and 0.066 cm² ster, 0.015 cm² ster correspondingly. Particle flux angular distributions are measured using a spacecraft rotation with a 2 min period around the axis directed to Sun (the angle 0°) and mechanical scanning of one measured during each of 2 min rotation period. Seven full scanning cycles will be carried out for every rotation. The first detector pair is fixed in the anti-solar direction. Moving detector pair can either scan from 45° to 180° (to sun direction) or can be set in one of 3 fixed positions: 45°, 90° and 135°. In a 15° position detector fields of view are covered and
detectors can be calibrated by Cd-109 internal conversion electron sources. We use proton flux detectors in the 22-28 keV range from the DOK-2 instrument.

4.2. Determination of Magnetosheath Intervals: Bow Shock and Magnetopause Crossings

Due to its orbit, Interball-1 travels in different parts of geospace from the geomagnetic tail (magnetosphere), to magnetosheath, to solar wind and back again. Figure 4.3 shows Interball-1 orbits in X-Z plane. Spacecraft passes the bow shock and magnetopause on an inbound trajectory or vice versa and sweeps the magnetosheath along each pass. It measures the characteristic parameters of each region, containing density, magnetic field, temperature, velocity, flux etc. For our purposes, we exclude both the solar wind and magnetospheric intervals by looking at the signatures of these parameters. High resolution data samples with the state-of-the-art instruments and longer duration of measurements make this study special over the earlier studies and give us a good opportunity to determine the magnetosheath structure.

In this study, we scanned Interball-1 magnetic field (MFI) and ion plasma (CORALL) and electron plasma (ELE) on the public web site from 1995 to 1998 in order to determine the times when the spacecraft is in the magnetosheath. Magnetosheath is the region between two boundaries: bow shock and magnetopause, which separate two different solar terrestrial environments, i.e. magnetosphere and solar wind (see also Section 2). It is filled with slower, denser and hotter shocked solar wind. Both bow shock and magnetopause show very distinct signatures in spacecraft data. Table 3 gives the field and plasma data signatures at the bow shock, magnetopause and in the magnetosheath for an inbound pass of Interball.

Figure 4.4 gives an example of time series of field and plasma parameters from August 26, 1997 to August 27, 1997 where crossing signatures were observed as the spacecraft moved from the solar wind into the magnetosheath. Figure 4.4a is the magnetic field components (nT) in GSE coordinates. Figure 4.4b shows ion density (#/cc), temperature (eV), and velocity components (km/sec) in GSE coordinates as well. While the top panel in Figure 4.4c presents the ion flux (#/cm²/s/keV/st), the bottom two panels give the electron density and temperature for
this interval. When there are multiple crossings, data have been selected accordingly. In this example, the spacecraft encounters the bow shock at around 16:00 in August 26, 1997 and the magnetopause has been observed at about 02:00 in August 27, 1997. Figure 4.5 shows the trajectory part corresponding to this time interval in x-R plane where R is $\sqrt{y^2 + z^2}$. Nominal bow shock and magnetopause locations have been overlayed in the figure.

For each trajectory of the spacecraft from 1995 to 1998, above characteristics have been looked for in order to decide when the spacecraft was in the magnetosheath. We determined total of 9599 magnetosheath crossings including the multiple crossings. The data resolution for all parameters are two minutes. Figures 4.6 through Figure 4.9 present the spacecraft coverage in the magnetosheath selected according to the criteria for 1995, 1996, 1997 and 1998 in x-R plane. To avoid the crowd of points, we have only plotted every 50 points in the figure. Model bow shock (Fairfield et al., 1990) and a model magnetopause (Roelof and Sibeck, 1993) for moderate solar wind conditions were overlayed in each plot. The figure shows that other than 1995, spacecraft has traversed magnetosheath many times and we have enough statistics for our study. The year of 1995 has fewer crossings because it only covers half of August, when the spacecraft launched, September and half of October months of the year. There are points inside model magnetopause or outside the model bow shock. However, this is due to the fact that the data include all solar wind plasma and field conditions. The data in this figure are not corrected for different solar wind pressures. We should also mention at this point that the time interval we study corresponds to the minimum solar activity periods.

In the following sections, we present results from our events(Cases) both in solar wind and in the magnetosheath in order to determine the effects of energetic particles using data selected as described above.

4.3. Case Studies in the Solar Wind

Case-1:

Figure 4.10 shows our first event in solar wind in July 30, 1996, from 14:00 to 19:30. Top panel (a) in the figure gives energetic particle flux measured in
#/cm²/s/keV/st. We use proton flux with energies between 22-28 keV from DOK instrument on board Interball. In the solar wind, CORALL plasma instruments do not work. Therefore, to compare with energetic particle data, here we used electron density and temperature. Although electrons and protons do not equally respond to the changes, especially in the magnetosheath, most of the time they present similar variations. Panels (b) and (d) give electron density and temperature in solar wind respectively. Panel (c) in Figure 4.10 displays the magnetic field variation. This interval in solar wind presents the relation between the parameters very clearly. Energetic particle flux exceeds well above 600-800 #/cm²/s/keV/st during the interval from 16:00 to 18:00. Electron density decreases and fluctuates corresponding to the presence of the energetic particles. Density stays low around 1.2 #/cc compare to the background (2 #/cc).

The magnetic field panel in Figure 4.10 shows the similar variations as in density. From 16:00 to 18:00 corresponding to the increasing high energy particle flux, magnetic field falls from values around 6 nT to 3 nT.

Temperature data shown in panel (d) do not show a clear relation in response to the increased particle flux level. However, a slight increase is evident in the figure. Variations in temperature field seem to increase as well.

Figure 4.11 presents the scatter diagrams for this interval. Top panel is for electron density and bottom panel is for magnetic field. The relation between the parameters and energetic particle flux is seen more clearly here. Density and magnetic field both show decreasing relation with increasing flux levels.

Interball-1 spacecraft is seen to be located on the dusk in the foreshock region on this day. Figure 4.12 gives the spacecraft trajectory in different planes. The time of the event shown in Figure 4.10 is marked in dark. During this interval, only x-component of magnetic field is available from Interball-1 and it shows a strong away-radial magnetic field in the solar wind. We used Wind spacecraft upstream of the Interball-1 to determine the IMF direction. Figure 4.13 gives magnetic field components from Wind. With an appropriate delay between the spacecraft, we can see that the IMF is mainly radial. The more radial the IMF in the solar wind is, the larger the foreshock region in front of the bow shock is (see Chapter 3.3 and Figure
31). Therefore, it appears that on this day, the energetic particles during this interval probably come from the foreshock.

**Case-2:**

Figure 4.14 displays our second solar wind case on day of March 27, 1996. Magnetic field and density both are lower corresponding to the high energy flux from 18:00 to 20:00 and 20:40 to 21:40. Peak flux levels vary above 1000 #/cm² s/keV/st. Temperature again do not show a particular variation during this interval.

Figure 4.15 gives the scatter diagrams for this case in the same format as in Figure 4.11. We see the anti-correlation with the increasing flux levels in density and magnetic field.

Figure 4.16 illustrates the Interball-1 orbits in different planes. In XY-plane, we see that the spacecraft is located on the dusk outside the bow shock. The IMF direction from the Wind spacecraft seen in Figure 4.17 shows moderate, extended toward-directed magnetic fields throughout the interval with some northward component.

**Case-3:**

Our third example in the solar wind given in Figure 4.18 is on the day of April 22, 1997. Time series plot in panels (a), (b) and (c) shows the anti-correlation of density and magnetic field with energetic particle flux. Scatter plots in Figure 4.19 support the decreasing relations in both parameters although it is not as clear as in the previous cases. In this example, the flux levels do not go up as high as in the previous two cases in which the peak flux reaches to about 3000 #/cm² s/keV/st. The peak flux is around 300 PFU. In all cases, temperature represents the most unpredictable variations in response to the changes in the flux levels. It seems like the relation is more clear if the flux level is above a threshold.

Figure 4.20 gives the spacecraft trajectory for this event. Interball-1 is seen on the dusk quadrant of the bow shock. We look at the magnetic field components from Wind spacecraft in order to predict the location of the Interball spacecraft with respect to the foreshock's nominal position. Figure 4.21 is the magnetic field components for this interval from the Wind spacecraft. It shows that the magnetic
field about two hours earlier variable but on the average toward-radial. It is highly probable that the spacecraft is in the foreshock in this example.

4.4. Case Studies in the Magnetosheath

In the previous section, we have seen high energetic particles changes the solar wind density and magnetic field. These effects due to the high energy particles backstreaming from the bow shock are in agreement with the earlier studies (Sibeck et al., 2001). In this part, we will show whether we can observe the similar relations in especially magnetic field and density due to the energetic particles in the region downstream of the bow shock, namely in the magnetosheath.

Case-1:

Figure 4.22 is the first example in the magnetosheath on the day of March 10, 1996 from 9:00 to 11:00. High fluxes are seen above 1000 #/cm²/s/keV/st. Since CORALL instrument is designed specifically for magnetosheath, we have density, velocity and temperature measurements for ions. In the figure, from top to bottom, proton flux, ion density, magnetic field strength, ion temperature and ion velocity are given respectively. In this figure, we see that high proton flux in the time interval from 09:00 to 10:30 for an extended time corresponds to lower density, magnetic field, and velocity. Temperature is seen to increase in this interval. Scatter plots for density and magnetic field are given in Figure 4.23. Although not very clear, a decreasing relation with high flux level in density is seen in this figure. This relation is more obvious in magnetic field panel.

Figure 4.24 gives the spacecraft location for this example. Spacecraft is located on the dusk side magnetosheath. Interball-1 was traversing from the magnetosphere into the magnetosheath. We looked at the Wind spacecraft magnetic field data with an appropriate solar wind travel time to Interball spacecraft to see the IMF direction upstream of Interball. Figure 4.25 shows the Wind spacecraft magnetic field measurements corresponding to this interval. All three components are presented. Wind spacecraft was located at about 140 Re while Interball-1 was about 10 Re toward the Sun on the x-direction. This gives about 20-30 min delay between two spacecraft. During corresponding time interval, the interplanetary magnetic field
switched in Bx component to a slight negative value about \(-1.5\) nT, and in Bz component to a strong negative Bz of about \(-5\) nT. By component was also strong and negative during this time with about \(-3\) nT. Although we need to do more analysis on the correlation with the IMF orientation, this interval seems to be associated with the IMF Bz component rather than Bx.

**Case-2:**

Figure 4.26 is the second example in the magnetosheath on the day of May 05, 1996. It gives the time series plot for proton flux, ion density, magnetic field strength and ion temperature. There were no velocity measurements for this interval. During this time, proton flux levels were measured above 4000 #:cm\(^2\)/s/keV/st. Corresponding to the increased higher level fluxes, a decrease in density and magnetic field is apparent. This decrease is followed by a slight increase in density following the fall of flux level to about. In this case, magnetic field and temperature show no particular variation.

Scatter plots given in Figure 4.27 verifies the time series plots. Magnetic field panel does not show any clear relation while a slight decrease is obvious in density panel. This decrease in density panel is apparent more clearly above a flux level of about 3500 #:cm\(^2\)/s/keV/st. The temperature scatter plot (not shown) again does not show any variation staying almost constant during the interval as in the time series plot.

Figure 4.28 is the trajectory plot of Interball-1 during this day. It traverses from the bow shock into the magnetosheath on the dusk hemisphere. The interplanetary magnetic field components from the Wind spacecraft are given in Figure 4.29. The solar wind travel time from Wind to Interval on this day is about 10 minutes. We have also looked at the solar wind plasma data for this case. Both solar wind plasma and magnetic field show no particular events. IMF is mainly radial oriented with relatively strong Bx component of about \(+5\) nT. By and Bz components are very small close to zero. Strong radial component is associated with the larger foreshock region (Le, 1991; Sibeck et al., 2001). Therefore the energetic particles in the magnetosheath that Interball observes in the magnetosheath might be associated.
with those accelerated at the bow shock. Again we need further analysis to confirm this option.

Case-3:

Figure 4.30 shows our last example in the magnetosheath on day April 06, 1996. The parameters are given in the same order as in Figure 4.22. Although the fluxes are not as high as in the other two cases, it ranges from very low values close to 1 to 1600 \#/cm²/s/keV/st. It is a good example to compare this with those in earlier higher flux cases. The magnetic field panel in panel (a) follows the changes in the flux in an inverse relation very nicely. Increasing flux intervals correspond to the decreasing magnetic field and in some order decreasing velocity while the inverse is true during decreasing fluxes. Density from 02:10 to 02:30 shows a slight decreasing tendency. We see that it fluctuates about 5 \#/cc. Prior to the increased flux level it was about 15 \#/cc. As in the earlier cases, temperature does not show a particular relation except that the fluctuations during the increasing flux intervals increased.

Scatter plots given in Figures 4.31 for this case reflect the changes we see in time series plots. Decreasing relation with increasing flux is not very clear on the density panel while magnetic field and velocity (not shown) show a more clear decrease with increasing flux levels.

Figure 4.32 gives the Interball-1 trajectory for this case. In this example, the spacecraft is seen entering the magnetosheath from the magnetosphere on the dusk quadrant. IMF shows a spiral angle in a toward sector with a magnitude of Bx about 1 nT and By about −1 nT. The interplanetary magnetic field components for this case are given in Figure 4.33 from the Wind spacecraft.

4.5. Statistical Analysis

4.5.1. Combined Cases

Figure 4.34 and 4.35 gives the combined results of the cases given in Sections 4.3 and 4.4. Figures include all IMF and solar wind plasma conditions. However, it serves to draw some general relation on the density and magnetic field structure in the magnetosheath.
Figure 4.34 presents all cases for density and magnetic field in the solar wind. As in earlier figures it gives the density and magnetic field variation with different energetic particle flux level. It is very clear that the low densities and low magnetic fields are associated with the high energetic particle flux in the solar wind. A linear curve fitted to the data gives a standard deviation as \( R = 0.68578 \) for density and \( R = 0.52627 \) for magnetic field.

Figure 4.35 shows the combined results in the magnetosheath density and magnetic field during the presence of the energetic particles. Although a slight decrease is noticeable in both parameters, this relation is not as strong as in Figure 4.34. A linear curve fitted to the data for this case gives a standard deviation as \( R = 0.059906 \) for density and \( R = 0.006984 \) for magnetic field. Thus, based on these, we conclude that we do not see any meaningful relation between the energetic particle flux and density and magnetic field in the magnetosheath as found in the solar wind.

On the case basis, we have examined 13 cases where the proton flux is above 200 \#/cm\(^2\)/s/keV/st in the magnetosheath. The result of this search is given in the Table 4.

Table 4 presents that among the other parameters, the magnetic field shows generally a decrease when the high energetic particles are present in the magnetosheath. Temperature does not show any clear relation although it does fluctuates during presence of the energetic particles. Density shows clear decreasing relation in some cases and increasing in the others as the energetic particle flux levels increase.

4.5.2. All Cases for Proton Flux > 500 keV

From the previous sections, we see that sometimes the relation between the density and magnetic field versus energetic particle flux can be extracted when the particle flux is above a flux threshold. In this part, we used all the available data above proton flux level of 500 FU in the dayside magnetosheath (X>0) from 1995 to 1998.
To understand the proton flux variation in the magnetosheath, Figure 4.36 is given. It is a histogram plot of all dproton flux data covering all years. Table 5 summarizes the dayside magnetosheath characteristics for all flux levels.

As seen in Figure 4.36, most of the data are clustered in the lower fluxes. We arbitrarily choose 500 PFU flux level. Histograms from Figures 4.37 through 4.46 show the distributions of ion density, magnetic field, ion temperature, and ion velocity. Top panels give distributions for proton flux > 500 PFU while bottom panels give distributions for proton flux < 500 PFU. Figures 4.47-4.49 give the normalized distributions for ion density, velocity, and temperature. These figures indicate that in the dayside magnetosheath, higher energetic particles are associated with the higher densities; with higher temperatures; and with higher velocities. However, this does not give how each of these parameters change with each other when the energetic particles are present in the magnetosheath. On the other hand, they may mean that because of this type of distribution, on the dayside magnetosheath, it may be difficult to observe cross-relations that we found in the upstream solar wind. That is, increasing proton flux versus decreasing density and magnetic fields is either too rare to find or more pronouncedly occur for specific conditions, like for example when there is foreshock region or for a specific IMF orientation.
5. CONCLUSION

5.1. Summary and Discussion

In the solar wind, using IMP-8, Wind and GEO spacecraft, Sibeck et al. (2001) presented the cases where density, magnetic field and temperature depress in the presence of high energetic particles. These regions, called HFAs, present the diamagnetic cavities in the solar wind and the associated pressure in them is lower. We have discussed in Section 3 that the variable solar wind pressures moves the magnetopause boundary in and out which can also seen in the ground magnetograms.

In this survey, we searched on whether similar structures can be seen in the dayside magnetosheath associated with the high energy particle flux. If we do not, how the high energy particles affect the magnetosheath density and magnetic field is the question we asked. The way that the energetic particles interact with the magnetosheath plasma and magnetic field can give us information on the interaction mechanisms between solar wind and magnetosphere. For this purpose, first we have searched Interball-1 solar wind data to show that a specific relation between the energetic particles and solar wind density and field in fact can be observed by Interball-1. Interball-1 data showed decreasing density and magnetic fields corresponding to the high energy particles in the upstream solar wind. These signatures agree with Sibeck's (2001) and Fairfield's (1990) findings.

Magnetosheath observations, however, are not clearly correlated with the high energy particles. It is clear that the high energy particles perturb all the parameters but a similar kind of relation as that in the solar wind is only present in the 60% of the events we studied. The rest of 40% show either opposite or no clear signature.

The reason why we do not see these events and their signatures in the magnetosheath may lie in the structure of the magnetosheath itself. The magnetosheath is a very turbulent environment owing to the solar wind plasma and field interaction at the bow shock. Its main characteristic is the fluctuating fields and plasma parameters in large amplitudes. High energy particles in the magnetosheath can predominantly come from two sources; foreshock or magnetosphere, more
specifically the plasma sheet. These particles perturb the field and plasma parameters. This fluctuating character is very clearly seen in time series plots presented in Section 4. In this case, the effects seen in the solar wind might be modified and altered at the bow shock if the high energetic particles coming from the foreshock region in such a way that the signatures we are looking for is different once the high energy particles enter the magnetosheath. In case of the magnetospheric source for the energetic particles, interaction at the magnetopause with these particles may modify and alter the field and density character of the magnetosheath.

The histograms and normalized plots given in Section 4.5 showed that individually the high density, high velocity and high temperature are seen in association with the high energetic fluxes. The opposite is true for low energy flux. Although these histograms or the normalized plots do not show the relation of each parameter to the other in the magnetosheath, it means that the events we are looking for in the magnetosheath are very rare despite the high number of high energy particle intervals.

Another factor is that Sibeck's events were observed during the bursts of high energy particles. In other words, both the duration of high energy particles in the solar wind is short and the energetic particle flux level is very high at this short time interval, like around 10000 PFU. In some of our cases too, we see better detectable relation when the flux level is above a threshold in the dayside magnetosheath.

Sibeck et al. (2001) observed their events in association with foreshock geometry and related IMF direction. In our study, IMF orientation has not been taken into account. This is our next search. IMF correlation should also provide us information on the connectivity of the magnetosheath events to the foreshock.

5.2. Conclusion and Future Work

In the solar wind, we find that the increasing high energetic particle flux decreases plasma density and magnetic field. Thus the energetic particles alters the solar wind pressure which in turn give rise to an outward motion of the magnetopause boundary. This is in agreement with the earlier studies.
In the magnetosheath, we find the relation between the energetic particle flux and magnetosheath density and magnetic field is not clear. On the case basis, we find a slight decrease both in density and magnetic field corresponding to high energy particle flux. However, it is difficult to generalize the relationship. We see that the high energy particles perturb the plasma and magnetic field so that the fluctuations are higher when there are high energy particles in the magnetosheath than when there are not or less. It seems these depressed density and magnetic field structure are more common in the solar wind than in the magnetosheath. We have discussed the possible reasons for this in Section 5.1.

Correlation with the IMF orientation should give us more on the interaction of high energetic particles with the magnetosheath plasma and field as their effects may be for some particular IMF directions. We will investigate both IMF and foreshock effects on the presence of high energetic particles and their influence in the magnetosheath structure.
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Table 1: Ranges of periods and frequencies in different pulsation classes
(Kivelson and Russell, 1995)

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Table 2: A list of instruments on Interball-1 spacecraft (Kremenov et al., 1996).

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<td>ADS</td>
<td>Nine-channel spectra-analyzer and cross-correlator, two-component measurements of current fluctuations, 0.1 Hz – 40 kHz.</td>
<td>J. Juchniewicz,</td>
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<td>Space Res. Center, Warsaw, Poland;</td>
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<td></td>
<td></td>
<td>L. Woolliscroft,</td>
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<td></td>
<td></td>
<td>Departm. of Contr. Engineering Sheffield Univ, Sheffield, UK;</td>
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<td></td>
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<td>S. Kilimov,</td>
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<td></td>
<td></td>
<td>IKI, Moscow, Russia.</td>
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<td></td>
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<td>V. Korepanov,</td>
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<td>SSD ASU, Lvov, Ukraine.</td>
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<tr>
<td>FGM-1</td>
<td>Measurements of 3D magnetic field 0–25 Hz in the range 0.25–258 nT. OPERA acquires and processes the data for SSNI.</td>
<td>J. Rustenbach,</td>
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<td></td>
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<td>MPE-A Berlin, Germany.</td>
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<td></td>
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<td>S. Savin,</td>
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<td>IKI, Moscow, Russia.</td>
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<tr>
<td>KEM-3 (aboard subsatellite)</td>
<td>Electric (0.1 Hz – 400 kHz) and magnetic (1-50 kHz) fields, two-component measurements of current fluctuations 0.1 Hz – 40 kHz.</td>
<td>P. Triska,</td>
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<td>F. Jiricek,</td>
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<td></td>
<td></td>
<td>Inst. Atm. Phys. CAS, Prague, Czech. Republic;</td>
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<td>S. Kilimov,</td>
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<td></td>
<td>IKI, Moscow, Russia.</td>
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<tr>
<td>EXPERIMENT</td>
<td>MEASURED PARAMETERS</td>
<td>PI AND KEY SCIENTISTS</td>
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<tr>
<td>FM-3I</td>
<td>Magnetic field (three components). Range: 0.2-200 nT; 0.5-1000 nT, Band: 0-10 Hz.</td>
<td>M. Nozdrachev, IKI, Moscow, Russia; V. Styazhkin, IZMIRAN, Troitsk, Russia</td>
</tr>
<tr>
<td>AKR-X</td>
<td>Radioemission in the range 100 kHz - 1.5 MHz.</td>
<td>L. Fischer, Komensky University, Bratislava, Slovakia; V. Grigorieva, Astron. Inst. of Moscow University, Moscow, Russia</td>
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<td><strong>ENERGETIC PARTICLES</strong></td>
<td></td>
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<tr>
<td>SKA-2</td>
<td>Charged energetic particles (E_p = 40-200) keV; (E_e = 0.05-150) keV) composition and anizotropy.</td>
<td>E. Morozova, E. Budnik, IKI, Moscow, Russia; S. Fischer, Astronomical Institute, Prague, Czech. Republic; E. Sarris, University of Thrace, Xanthi, Greece</td>
</tr>
<tr>
<td>DOK-2</td>
<td>Energy spectra, angular distributions and time variations of electrons (E = 15-400) keV) and ions (E = 20-1000) keV).</td>
<td>K. Kudela, Institute of Experim. Physics. SAS, Kosice, Slovakia; V. Lutsenko, IKI, Moscow, Russia; E. Sarris, University of Thrace, Xanthi, Greece</td>
</tr>
<tr>
<td>RF-15-I</td>
<td>Solar X-ray burst spectra and time profile measurements in the range 2-240 keV; the data are processed by PRAM.</td>
<td>O. Likin, IKI, Moscow, Russia; F. Farnik, Astr. Inst. CAS, Ondrejov, Czech. Republic; J. Sylvester, Space Res. Center, Wroclaw, Poland</td>
</tr>
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</table>
Table 2: Cont.

<table>
<thead>
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<th>EXPERIMENT</th>
<th>MEASURED PARAMETERS</th>
<th>PI AND KEY SCIENTISTS</th>
</tr>
</thead>
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<tr>
<td>1</td>
<td>2</td>
<td>3</td>
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<tr>
<td>SOSNA-3</td>
<td>Dosimetric measurements.</td>
<td>V. Bengin, V. Patrov, IMBP, Moscow, Russia. S. Kuznetsov, Moscow University, Moscow, Russia.</td>
</tr>
<tr>
<td>RKI-2</td>
<td>Ionizing radiation (5, 15, 40, 100, 500 MeV) and UV radiation from the Sun.</td>
<td>T. Kazachevskaya, IPG, Moscow, Russia.</td>
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<tr>
<td><strong>SERVICE SYSTEMS</strong></td>
<td></td>
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<tr>
<td>BNK, BNTR BNTS</td>
<td>Commutation blocks</td>
<td>T. Lessina, IKI, Moscow, Russia.</td>
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<tr>
<td>SSNI</td>
<td>Telemetry system.</td>
<td>L. Chesalin, IKI, Moscow, Russia.</td>
</tr>
</tbody>
</table>
Table 3: Bowshock, magnetopause and magnetosheath signatures in various parameters for an inbound Interball-1 pass on August 27, 1997.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>At the bow shock / In the magnetosheath</th>
<th>At the magnetopause / In the magnetosphere</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion Density</td>
<td>Sharp increase / high values</td>
<td>Sharp decrease toward zero values / zero</td>
</tr>
<tr>
<td>Ion Temperature</td>
<td>Increase / relatively high with respect to solar wind, stable variation around 100 eV</td>
<td>Sharp increase / very high values</td>
</tr>
<tr>
<td>Ion Velocity Magnitude</td>
<td>Decrease (predominantly x-component, values around 200 km/sec, depending on the latitude) /low and more stable with respect to solar wind</td>
<td>Decrease to very low values</td>
</tr>
<tr>
<td>Electron Density</td>
<td>A sharp increase / very high values</td>
<td>Sharp decrease / drop to zero values</td>
</tr>
<tr>
<td>Electron Temperature</td>
<td>Increase to values around 100 eV / variation is more stable</td>
<td>Sharp increase to above 1000 eV</td>
</tr>
<tr>
<td>Magnetic field Strength</td>
<td>A sharp increase / fluctuating components</td>
<td>A very strong increase / stable variation</td>
</tr>
<tr>
<td>Ion Flux</td>
<td>Gradual increase while fluctuating, then slightly lower and more stable variation</td>
<td>Sharp drop to zero, and no observation beyond due to the instrument's characteristics</td>
</tr>
</tbody>
</table>
Table 4: Relation between magnetosheath magnetic field, density, temperature, and energetic particles for 13-cases when proton flux is above 200 #/cm$^3$/s/keV/cases

<table>
<thead>
<tr>
<th>N=13 cases</th>
<th>Negative Relation</th>
<th>Positive Relation</th>
<th>Not Clear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux-Density</td>
<td>3</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>Flux-Magnetic field</td>
<td>9</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Flux-Temperature</td>
<td>3</td>
<td>-</td>
<td>10</td>
</tr>
</tbody>
</table>
Table 5: Magnetosheath characteristics for all flux levels

<table>
<thead>
<tr>
<th>Parameter</th>
<th># of Data</th>
<th>Max</th>
<th>Min</th>
<th>Mean</th>
<th>Median</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron Flux (21-26 keV)</td>
<td>30275</td>
<td>4090</td>
<td>0.0124</td>
<td>7.885</td>
<td>0.49</td>
<td>89,217</td>
</tr>
<tr>
<td>Electron Flux (76-95 keV)</td>
<td>10178</td>
<td>11740</td>
<td>0</td>
<td>2.125</td>
<td>0.191</td>
<td>26,207</td>
</tr>
<tr>
<td>Proton Flux (22-28 keV)</td>
<td>30314</td>
<td>26200</td>
<td>0.0484</td>
<td>212.06</td>
<td>3.89</td>
<td>938,21</td>
</tr>
</tbody>
</table>
| Ion Density (#/cc)            | Ni        | 20600   | 113.51  | 0.009  | 9.8922  | 6.241              | 10,908
| Ion Temperature (eV)          | Ti        | 20600   | 11497   | 20.6   | 196.53  | 164.65             | 265,82
| Ion Velocity X (km/sec)       | Vx        | 20598   | -1431.5 | 637.6  | -86.212 | -115.3             | 119,87
| Ion Velocity Y (km/sec)       | Vy        | 18422   | 811.79  | -808.43| 22.676  | 13.067             | 121,82
| Ion Velocity Z (km/sec)       | Vz        | 18422   | 862.37  | -611.2 | 33.507  | 76.984             | 122,59
| Ion Velocity (km/sec)         | Vtot      | 18422   | 1440.2  | 22.067 | 220.2   | 220.21             | 76.4
| Magnetic Field X (nT)         | Bx        | 31574   | 76.26   | -78.97 | 1.2627  | 1.57              | 9,1526
| Magnetic Field Y (nT)         | By        | 26458   | 110.78  | -78.924| -2.9072 | -4.2405           | 15,562
| Magnetic Field Z (nT)         | Bz        | 26458   | 68.912  | -80.463| -1.5424 | -1.3987           | 13.56
| Magnetic Field (nT)           | Btot      | 31574   | 136.46  | 0.49487| 20.24   | 18.134            | 11.416

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Figure 2.1: A schematic showing the interaction ways between the Sun and Earth's atmosphere (modified from Kaymaz, 1996 and Tulunay 2001)
Figure 2.2: A chart showing the relation between the Sun and the Earth's atmospheric layers (Adapted from Kaymaz, 1996)
Figure 2.3: A sketch showing the Earth's solar terrestrial environment (Adapted from Kaymaz, 1996)
Figure 2.4: A three-dimensional sketch showing the elements of solar-terrestrial coupling (Rycroft, 1989)
Figure 2.5: Spacecraft observations of a strong shock (Kivelson and Russell, 1995)
Figure 2.6: A three dimensional illustration of solar-terrestrial environment (Tascione, 1980)
Figure 2.7: Schematic view of an open magnetospheric model (Dungey, 1961)
Figure 2.8: Schematic view of a closed magnetospheric model (Dungey, 1961)
Figure 2.9: A time series example of substorm showing the energy deposited into the Earth's upper atmosphere as joule heating on March 22, 1979 (Tascione, 1994)
Figure 2.10: Cross section of the magnetosphere showing the principal currents (Tascione, 1989)
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Figure 2.12: Examples of Pi (top panel) and Pc (bottom) events recorded on the ground (Parks, 1991)
Figure 2.13: Examples of approximately 1-min waves in magnetosphere (top) and on the ground (bottom) at stations whose latitude are indicated to the right (Kivelson and Russell, 1995)
Figure 2.14: A sketch showing the location of the magnetopause and bow shock location in response to a variable solar wind pressure (Adapted from Kaymaz, 1996)
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Figure 2.15: Same as Figure 2.15 b (Continue).
Figure 2.15: Same as Figure 2.15 b (Continue).
Figure 3.1: Foreshock geometry and IMF orientation (Le, 1991)
Figure 3.2: Time series example showing the effects of upstream waves on the solar wind pressure, magnetic field, density and velocity (Fairfield et al., 1990)
Figure 3.3: Time series example showing the magnetic field and density variation in foreshock (Fairfield et al., 1990)

Figure 3.4: Time series plot of magnetic field, temperature and velocity in the upstream solar wind showing the hot deflected flow region (Fairfield et al., 1990)
Figure 3.5: A sketch of a moving boundary in response to an increase in magnetosheath pressure. Layers marked as 1, 2, 3, 4 shows magnetosheath, LLBL, depletion layer and energetic particle layers and magnetosphere respectively. Magnetopause lies between layers 2 and 3 (Sibeck, 1992).
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**Figure 3.7**: An equatorial cross-section of the magnetopause disturbance (Sibeck, 1990).
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Figure 3.10: Time series example of magnetopause boundary motion as seen in plots of plasma thermal pressures (ion, electron and their sum), the magnetic and total (plasma and magnetic) pressures, the ion and electron temperatures, the ion (solid curve) and electron (dashed) densities, and magnetic field strength from 11:50 to 12:20 UT on October 28, 1984. A bar across top shows the magnetospheric, magnetosheath, and boundary layer regions (Sibeck, 1992).
Figure 3.11: Another time series example of magnetospheric boundary motion from 10:43 to 10:49 on October 28, 1984. Magnetic field signatures are given in the figure L, M and N denotes the north-south, east-west and x-components of the field (Sibeck, 1992).
Figure 3.12: Same as Figure 3.11 but for electron and ion densities, the fluxes of energetic electrons and ions, the electron and ion temperatures, and the ion velocity on the same day (Sibeck, 1992).

Figure 3.13: The observations of thermal, magnetic, and total pressures corresponding to the data given in Figures 3.11 and 3.12 (Farrugia et al., 1988; Sibeck, 1992).
Figure 3.14: The plasma and magnetic field measurements on a pass from magnetosheath to magnetosphere (Safranovka et al., 1997).
Figure 3.15: Schematic drawing of the magnetopause motion to explain the data seen in Figure 3.14 (Safrankova et al., 1997).
Figure 3.16: Time series examples of magnetosheath crossings with and without upstream waves (Formisano et al., 1973).
Figure 3.17: The histograms of normalized magnetosheath density, thermal speed and bulk velocity to their upstream values (Formisano et al., 1973).
Figure 3.18: Crater-like structures in the magnetic field strength and solar wind density as in the kinetic hybrid simulation of Thomas and Brecht (1988).
Figure 3.19: A schematic model showing the effects of waves driven by pressure variations produced in the foreshock (Sibeck et al., 2000)
Figure 3.20: An example from Sibeck et al. (2001) showing the energetic particle effects on the solar wind parameters on January 8, 1995.
Figure 3.21: Scatterplots of velocity, temperature, and magnetic field strength versus density corresponding to the event given in Figure 3.20 (Silbeck et al., 2001).
Figure 3.22: Scatterplots of IMP-8 magnetic field, density, velocity, and temperature versus energetic particle flux intensity on January 8, 1995 (Sibeck et al., 2001).
Figure 3.23: Projection of the locations where IMP-8 spacecraft observed energetic particles in the solar wind from January 1 to August 31, 1995. Overlayed on it is the schematic model to explain the observation given in Figures 3.19-3.22 (Sibeck et al., 2001).
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Figure 4.2: Schematic view of Interball-1 spacecraft with its instruments (Kremnev et al., 1996).
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Figure 4.4b: Same as Figure 4.4a but density, temperature and velocity components on August 26.
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Figure 4.5b: The Interball-1 coverage in the magnetosheath for 1995.
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Figure 4.5d: The Interball-1 coverage in the magnetosheath for 1997.
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Figure 4.6: Time series plots of solar wind parameters. From top to bottom, energetic particle flux, density, magnetic field, and temperature corresponding to Case-1.
Figure 4.7: Scatterplots corresponding to Figure 4.6
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Figure 4.9: Magnetic field components from Wind spacecraft for Cass-1 in the upstream solar wind on July 30, 1997.
Figure 4.10: Time series plots of solar wind parameters. From top to bottom, energetic particle flux, density, magnetic field, and temperature corresponding to Case-2.
Interball-1
27/03/1996 18:00-23:00

Electron Density (no/cc)

Proton Flux (PFU)

Total Magnetic Field (nT)

Figure 4.11: Scatterplots corresponding to Figure 4.10.
Figure 4.12: Interball-1 trajectory for Case-2 in solar wind.
Figure 4.13: Magnetic field components from Wind spacecraft for Case-2 in the upstream solar wind on March 27, 1996.
Figure 4.14: Time series plots of solar wind parameters. From top to bottom, energetic particle flux, density, magnetic field, and temperature corresponding to Case-3.
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Figure 4.17: Magnetic field components from Wind spacecraft for Case-3 in the upstream solar wind on April 22, 1997.
Figure 4.18: Time series plots of magnetosheath parameters. From top to bottom, energetic particle flux, density, magnetic field, velocity and temperature corresponding to Case-1.
Figure 4.19: Scatterplots corresponding to Figure 4.18.
Figure 4.20: Interball-1 trajectory for Case-1 in the magnetosheath.
Figure 4.21: Magnetic field components from Wind spacecraft for Case-1 in the magnetosheath on March 10, 1996.
Figure 4.22: Time series plots of magnetosheath parameters. From top to bottom, energetic particle flux, density, magnetic field, velocity and temperature corresponding to Case-2.
Figure 4.23: Scatterplots corresponding to Figure 4.22.
Figure 4.24: Interball-1 trajectory for Case-2 in the magnetosheath.
Figure 4.25: Magnetic field components from Wind spacecraft for Case-2 in the magnetosheath on May 5, 1996.
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Figure 4.27: Scatterplots corresponding to Figure 4.26.
Figure 4.28: Interball-1 trajectory for Case-3 in the magnetosheath.
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Figure 4.30: Scatterplots for all Cases (Case-1, Case-2 and Case-3) in solar wind.
Figure 4.31: Scatterplots for all Cases (Case-1, Case-2 and Case-3) in the magnetosheath.
Interball-1

Energy (22-28 keV)

Proton Flux (PFU)

Number of Data

PFU = no / cm² / s / keV / st

Figure 4.32: Histogram for all flux levels in all data.
Figure 4.33: Histograms of ion density for proton flux $>500$ PFU and $<500$ PFU.
Figure 4.34: Same as Figure 4.33 but for total magnetic field.
Figure 4.35: Same as Figure 4.33 but for x-component of the magnetic field.
Figure 4.36: Same as Figure 4.33 but for y-component of the magnetic field.
Figure 4.37: Same as Figure 4.33 but for z-component of the magnetic field.
Figure 4.38: Same as Figure 4.33 but for temperature.
Figure 4.39: Same as Figure 4.33 but for total velocity.
Figure 4.40: Same as Figure 4.33 but for x-component of velocity.
Figure 4.41: Same as Figure 4.33 but for y-component of velocity.
Figure 4.42: Same as Figure 4.33 but for z-component of velocity.
Figure 4.43: Normalized distribution of ion density for proton flux >500 PFU and <500 PFU.
Figure 4.44: Same as Figure 4.43 but for velocity.
Figure 4.45: Same as Figure 4.43 but for temperature.
VITA

Education

2000-2002 Graduate Student in Department of Meteorological Engineering, Faculty of Aeronautics and Astronautics, Istanbul Technical University, Istanbul-Turkey
1995-1999 BSc in Department of Meteorological Engineering, Faculty of Aeronautics and Astronautics, Istanbul Technical University, Istanbul-Turkey

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July 1999 Graduated as Third in class of 1999 (among 20 students)

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Sept 1998-June 1999 BSc project on Meteorological Applications in Military

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1997, Summer Synoptic Meteorology Training at the Goztepe Meteorological Station, Istanbul-Turkey
1996, Summer Climatology Training on Bahcekoy Meteorological Station, Istanbul-Turkey