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OBSERVATIONS OF MAGNETOSHEATH
PLASMA AT THE LUNAR ORBIT

by
Martha Ann Fenner

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

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CHAPTER I

INTRODUCTION

The interaction of the solar environment with the earth and its magnetic field has become a separate field of research in recent years. The purpose of this endeavor is to describe the earth's particle and field environment and the influences upon it from the solar environment in which it travels. The interface between these two environments is a transition region called the magnetosheath. The magnetopause which encloses the earth's magnetosphere is the boundary of pressure balance between the earth's particles and fields and those of the sun. The bow shock wave is a boundary formed upstream of the pressure boundary to stand off the supersonic solar wind flow. The magnetosheath, lying between the two boundaries, is a region in which deflected solar wind flows around the magnetosphere (see Figure 1.1). The purpose of this paper is to present particle data taken in the magnetosheath at a distance of 60 R_e from the earth. The experiment involves 3 charged particle detectors included in the scientific package of instruments deployed on the moon's surface during the Apollo missions. It is hoped that these observations of the distant interaction region will contribute to a growing understanding of the turbulent magnetosheath and its dynamic processes.

First we present an historical review of the development of the basic concepts of the interaction region: the bow shock the magnetosheath, and the magnetopause.
Figure 1.1  A summary of typical plasma and magnetic properties in the solar wind, the magnetosheath and the outer magnetosphere (after McKenzie, 1970).

Figure 1.2  Interplanetary plasma flow in a plane containing neutral points according to the theory of Dungey (after Dungey, 1961).
Then the present knowledge concerning them is summarized in two parts; 1) the topology of the interaction region and 2) the dynamic processes leading to this configuration.

1.1 HISTORICAL DEVELOPMENT

The earliest conception that the earth's dipole field was confined by solar plasma was suggested by Chapman and Ferraro in 1931. They associated the earth's magnetic storms with bursts of charged particles from solar flares. Approaching the earth, these particles would be deflected by the earth's magnetic field. An electric current would be set up in the deflection boundary because oppositely charged particles are deflected in opposite directions. The diamagnetic effect of the current would enhance the near earth field and cancel the effect of the dipole field in the plasma so as to exclude particles from the earth's field and form a cavity in the plasma. This early concept which successfully explained the initial phase of magnetic storms is basic to the interaction theory today. It was not realized until later that solar plasma is emitted continuously and the resulting cavity is a permanent configuration of the earth's environment.

The first in situ observations of the interaction region came almost twenty years later and was shortly followed by more extensive theories. Pioneer I launched in 1958 reported a drop in the geomagnetic field along the earth-sun line at 13.8 Re (Sonett, et. al., 1960). This confirmed the proposed confinement of the geomagnetic field although the boundary observed was probably the bow shock
rather than the magnetopause. Explorer 10, launched in March, 1961, in an anti-solar direction, confirmed the absence of plasma in a geomagnetic cavity to a distance of 40 $R_e$ (Bonetti, et al., 1963). Then it observed a region of anti-solar streaming plasma which was excluded from the geomagnetic cavity. This was probably the first magnetosheath observation.

Explorer 10 confirmed that the solar plasma was supersonic as had been suggested by Parker (1958). This result suggested the necessity of a standing shock wave upstream from the geomagnetic cavity (Kellogg, 1962). Explorer 12, launched in August 1961, observed a plasma enhancement at the magnetopause and then a disappearance of high energy electrons at 10 $R_e$ (Freeman, 1964). This was the first confirmation of the proposed bow shock.

As observations became more extensive, new models of the magnetosphere were proposed. Dungey (1961) proposed a model of the interaction whereby the interplanetary field lines connected with those of the earth's dipole. Figure 1.2 shows the interplanetary field in which the earth's dipole is threaded. This model gives the solar wind particles access to the earth through the polar cusps. It requires a southward interplanetary field perpendicular to the ecliptic in order for the field lines to be connected. For this case, interplanetary particles can flow through the tail into the region of the auroral zones. Such an influx of particles was suspected as a trigger to magnetic storms. Consequently, observations of a direct correlation between a southward component of the interplanetary field and magnetic storms
has been very important (Shatten and Wilcox, 1967). Dungey's model may be referred to as open because of the field line connection and direct particle access. Petschek (1964) has worked on the details of field line merging required in the tail, and many others have extended the details of this model.

Another, totally different concept of the magnetosphere was proposed by Axford and Hines (figure 1.3) following the model of Beard and Mead (1964) in which the geomagnetic field lines are not connected to interplanetary field lines. In this closed system the tail is drawn out by viscous forces on the flanks of the magnetosphere. Axford (1964) suggested magnetosonic waves reflecting at the magnetopause as a source of the viscous interaction. Dessler suggested a very long tail sustained by the pressure of hydromagnetic waves, which has indeed been observed.

Although the controversy between an open or closed magnetosphere is being resolved in favor of an open model, it is pedagogically important to consider both models. Tenets from each will probably be included in a detailed understanding of the interaction region. For example, the hydromagnetic waves that were first suggested as a part of the closed magnetosphere model must be considered in a detailed balance of energy across the magnetosheath boundaries (Asseo and Berthomieu, 1970). Therefore, waves and instabilities must be included in a comprehensive model of the magnetosheath even though they do not necessarily lend credibility to a closed model.

After the confirmation of the existence of the bow shock wave, the magnetopause and the magnetosheath, the number of satellite observations increased rapidly. Theories became
Figure 1.3  A theoretical model of the tail of the magnetosphere. Friction at the magnetopause pulls the field lines back and produces a neutral sheet (after Axford et al., 1965).
more extensive. Rather than continue a chronological development of theory and observations, we will present a summary of current knowledge. Research in the magnetosheath seems to move in two basic directions: a description of the general configuration (or topology) of the magnetosheath, and an understanding of its dynamic processes. Certainly the processes are the explanation for the resulting configuration. However, we generally describe the physical situation as accurately as possible and then ask why it exists as it does.

1.2 TOPOLOGY OF THE MAGNETOSHEATH

MAGNETOPAUSE.

The pressure balance boundary of the magnetosphere has been observed to be a tangential discontinuity in the field. The dipole field on the inside is in a different direction from the interplanetary field on the outside, but both are parallel to the plane of the boundary. There is no normal component of the field at the boundary (Cassen, 1970). Also the fluctuations in the field are enhanced outside the boundary.

Transverse random motion of the magnetopause boundary has two components, one having a 15 to 30 minute periodicity (Freeman, et al., 1967), and the other having a 1 hour periodicity (Howe, 1971). The position of the magnetopause is directly related to geomagnetic and solar conditions. A distant magnetopause always indicates quiet geomagnetic conditions, but a close-in magnetopause may indicate either
quiet or disturbed conditions. At the lunar distance the boundary varies from 30 to 1000 km in thickness and oscillates at a speed in excess of 1 km/sec (Mihalov et al., 1970).

An empirical equation for this boundary was derived by Howe (1971) in solar magnetospheric coordinates adjusted to solar wind direction \( Y = 23.9 \tan^{-1} \sqrt{\frac{10.0 - X}{15.9}} \). This equation is applicable out to the lunar distance.

**Bow Shock**

A shock wave is formed upstream of the magnetopause some 3 or 4 \( R_E \) (at the subsolar point) to stand off the supersonic solar wind. The shock front itself is several 10's of kilometers thick and has a waving motion with an average velocity of 8 to 10 km/sec (Montgomery et al., 1970). Plasma parameters are seen to vary considerably across the shock wave. The temperature is increased and the bulk velocity is decreased. The temperature jump across the shock is 2 to 4 times greater for ions than for electrons (Montgomery et al., 1970). Rankine-Hugoniot equations for parameter jumps across a shock wave are satisfied at the bow shock (Howe, 1970).

Greenstadt (1972) developed a binary index to determine the type of shock structure. He defined two types of shocks; 1) perpendicular and 2) oblique. These were classified according to the angle of the interplanetary field with respect to the shock propagation. An oblique shock or pulsation shock is accompanied by fluctuating fields and random proton spectra. As seen in Figure 1.4, the two types of structure may occur
A comparison of the oblique ($I_p = 1$) and perpendicular ($I_p = 0$) shocks occurring simultaneously at the earth's bow shock wave for the 45° interplanetary field configuration shown (after Greenstadt, 1972b).
simultaneously on opposite sides of the magnetosphere and represent quite different phenomena. Greenstadt (1972) reports 50% more oblique shocks on the dawn side. Howe observed twice as many shock crossings on the dawn side and Fairfield (1971) observed the dawn field to be more disturbed than the dusk field. Therefore, there is strong evidence for an asymmetry of the two sides of the magnetosheath.

Again we use Howe's empirical equation for this boundary out to the lunar distance.

\[
\frac{(x-191.2)^2}{(177.7)^2} - \frac{y^2}{(56.7)^2} = 1
\]

This is a hyperbola fit to Explorer 33 data in solar magnetospheric coordinates, oriented in the solar wind flow direction.

**INSIDE THE SHEATH**

Flow parameters in the magnetosheath were calculated by Spreiter and Jones as early as 1963 using gas dynamics. Lees (1964) extended these calculations to include the magnetic field. The hydromagnetic theory of Spreiter and Alksne (1969) has been compared to observations (Howe, 1972) and has shown very good agreement with observations. These calculations were not extended as far back as the Moon's orbit. In order to apply the theory at this distance, the particle pressure inside the magnetosphere and field pressure outside can no longer be ignored. Flow parameters in the various regions from the nose to the tail are shown in Figure 1.1.
A change in the internal energy of the plasma is reflected by the decrease in temperature and increase in velocity as it flows to greater distances behind the earth. At a position 60° downstream from the dawn-dusk meridian the flow has been observed (Hundhausen et al., 1970a) to be supersonic again in the sheath, although the velocity is less than that of the incident solar wind. Further downstream, the density inside the shock becomes less than the pre-shock density.

A summary of a typical magnetosheath traversal as recorded by Pioneer 6 (Wolfe and McKibbin, 1968) is given in Figure 1.5. The general trend of the velocity and density to increase going outward across the sheath from the magnetopause to the bow shock is apparent. Also the temperature will generally decrease across the sheath, as predicted in gas-dynamic theory.

From satellite particle data (Figure 1.6) the magnetosheath may be characterized by its plasma energy spectra which are quite distinct from those of the solar wind in the following ways:

1) The peak energy is somewhat lower than in the solar wind.

2) Random motion has increased with respect to the bulk flow, i.e. temperature has increased.

3) No \( \text{He}^{++} \) peak is distinguishable in the broad spectrum.

4) The spectrum is non-Maxwellian because of an enhancements of high energy particles.
Figure 1.5  The magnetic field, ion velocity, ion density, components of ion flow direction and electron temperature, shown as a function of time in UT and geocentric distance in Earth radii for the Pioneer 6 magnetosheath traversal of 16 December 1965 (after Wolfe and McKibbin, 1968).

Figure 1.6  Energy spectra and angular distributions of solar plasma measured by Vela in the interplanetary medium and magnetosheath (after Bame et al., 1967).
FIGURE 1.5
FIGURE 1.6
The magnetic field in the sheath ranges from \( \sim 20\gamma \) to \( \sim 13\gamma \) across the sheath from the magnetopause to the bow shock (Wolfe, 1968). Fluctuations of this field will be considered in the next section, dealing with processes in the sheath.

1.3 DYNAMIC PROCESSES OF THE MAGNETOSHEATH

The gas dynamic theory of Spreiter and Alksne is able to explain the general topology of the sheath. It accounts for the changes in the flow parameters across the sheath (Howe, 1971), and the general field configuration. The success of this theory is limited, however. It is not adequate to explain the presence of a high energy tail rather than a pure Maxwellian distribution function, i.e., the excessive turbulence in the sheath. These specific observations are important in treating the still unanswered problem of energy transport in the magnetospheric interaction. Two approaches to the energy transport problem are 1) magneto-hydrodynamic coupling in the plasma-filled transition region and 2) direct access of solar plasma into the magnetosphere. First we will discuss the energy transport problem. Then a summary of work done to solve the problem using each of the two approaches will be presented.
ENERGY TRANSPORT PROBLEM

Geomagnetic storms are expensive magnetospheric phenomena requiring energies in the range of $\sim 10^{18}$ erg/sec (aurorae) or $\sim 10^{18}$ to $10^{19}$ erg/sec (ring current) to sustain them. These phenomena have been observationally linked to solar phenomena for some time. The solar wind which carries energy from the sun intercepts the earth's magnetosphere. It is generally accepted as the energy source for storms. A large quantity ($10^{20}$-$10^{22}$ ergs/sec) of solar wind energy is incident on the surface of the magnetosphere (Ershkovich, 1970). Thus, it is adequate to support geomagnetic storms. The question remains as to how the energy is transferred to the magnetosphere. The two directions in which the problem is being approached stem from the open and closed magnetospheric models discussed earlier. The viscous interaction of Axford's closed model was suggested to transport energy across the magnetopause by the refraction of hydromagnetic waves at the boundary. Instabilities in both boundaries and wave particle interactions inside the sheath were also considered as to their contribution to a magnetohydrodynamic coupling of energy across the transition region. The second approach considered the entry of solar wind particles into the magnetosphere, which was allowed by Dungey's open model.

MAGNETOHYDRODYNAMIC COUPLING

Particle and field experiments have long reported turbulence in the magnetosheath. Power spectral density analyses of data in the sheath usually indicate a smooth
distribution of power over all frequencies rather than waves peaked at certain frequencies. By properly separating out the significant components, the types of waves present in the sheath may be classified. Kaufmann (1970) used a wave-oriented coordinate system to define waves observed by the Explorer 12 magnetometer. He reported that magnetoacoustic waves in the frequency range of .01 to .1 hertz dominate the disturbed magnetosheath. Rotational Alfvén waves are seen below .01 hertz. From the location of the observations with respect to the boundaries, Kaufmann concludes that magnetoacoustic waves are produced or amplified in the bow shock or outer magnetosheath. Rotational waves may be carried into the sheath by the solar wind.

Further theoretical evidence that interplanetary disturbances are transmitted across the bow shock has been worked out by Jaggi (1971). He discusses five types of disturbances in solar wind parameters that will appear in the sheath. Asseo (1970) shows that a single hydromagnetic wave incident on the bow shock gives rise to five refracted waves in the sheath. There is amplification in at least one of these refracted waves.

Thus, the coupling of energy across the shock wave has been resonably well established. The jump parameters across the shock have been measured and compared to Rankine-Hugoniot equations. It has been found (Chao, 1972) that extra energy and momentum terms due to turbulence must be added in order to satisfy the shock relations precisely.
The next problem is the coupling of energy across the sheath and then into the magnetosphere. Landau damping is expected behind the shock (Hess, 1968) and wave-particle interactions are presumably responsible for the absorption of waves in the inner sheath. Kaufmann did not observe magnetoacoustic waves far inside the shock. The energy is apparently dumped into the particles which might be expected to diffuse in velocity space.

Transmission of energy across the magnetopause has been investigated theoretically. Verzariu (1972) calculates a transmission coefficient of 1-2% for MHD waves of frequencies greater than .1 hertz. This range is above that of most experimental work. McKenzie's (1970) theory proposes the magnetopause to be a near perfect reflector near the nose, but this has not been investigated experimentally. A correlation of disturbances in the sheath to those in the magnetosphere is expected, but has not been observed.

The motion of the magnetopause (Howe, 1972) suggests that a Kelvin-Helmholtz instability is present in the boundary itself. This instability depends on the angle of flow in the sheath with respect to the boundary. Other instabilities are probably present inside the sheath. An ion-ion counterstreaming instability (Eviatar, 1968) in the bow shock is thought to account for heating the ions as they cross the shock. The presence of an instability in the shock is also indicated by high energy particles flowing upstream in the solar wind (Montgomery, 1970).
Turbulence in the particle data is usually indicated by unstable spectra on a very short time scale. Multiple peaks at high energies are observed near the bow shock (Neugebauer, 1971). These fluctuating high energy peaks in the 24 second spectra result in a high energy tail when averaged over 20 minutes. The diffusion of particles in velocity space forming a high energy tail is a measure of turbulence in the sheath. Formisano (1973) correlated the presence of a high energy tail with the absence of upstream waves in the solar wind. Thus, sheath turbulence has been correlated with interplanetary conditions but not with geomagnetic conditions.

The mechanism producing a high energy tail has not been thoroughly explained. Three processes have been suggested to accelerate particles in the sheath: wave particle interactions, stochastic acceleration and fermi acceleration. Only wave-particle interactions have been referred to so far. Landau damping is perhaps the most straightforward way of transferring energy from the waves to the particles. The rate of change of the energy depends on the slope of the distribution function as can be seen in the following equation:

\[
\frac{d}{dt} \frac{mv^2}{2} = -\frac{nwe^2B^2}{2m|k|^2} \left( \frac{\partial f(V_o)}{\partial V_o} \right) V_o = \frac{w}{k}
\]

This is taken only from a velocity \( V_o \) close to the phase velocity of the wave \( \frac{w}{k} \). If the slope is negative, energy is transferred to the particles. In the case of a positive slope as in a spectrum of multiple high energy peaks, the energy will be given up to a wave, flattening out the high energy peak. This mechanism could produce a high energy tail.
Stochastic acceleration is a process which will accelerate a few particles to high energies as a result of a time varying electric field. Sturrock (1966) worked this out for the case of acceleration parallel to the magnetic field and for cyclotron acceleration transverse to the magnetic field. He showed that both result in a Maxwellian distribution at a high energy. He suggested this as a mechanism to produce the high energy (10-30 kev) electrons observed in the sheath. This mechanism probably does not contribute to the high energy tail of the protons.

The third acceleration mechanism, Fermi acceleration was first considered by Parker (1958a) as a possible mechanism in the sheath. It involves the interaction of particles with moving magnetic mirrors. The application in the magnetosheath would be the reflection of a particle between an interplanetary field disturbance and the increased magnetic field at the magnetopause. Parker showed that this mechanism results in a distribution function having a high energy tail:

\[ f(v) = \frac{1}{\sqrt{2\pi}} \frac{2k}{m} \exp \left( \frac{-v}{v_{SW}} \right) \]

This mechanism could contribute to high energies in the sheath. However, the angle of the interplanetary field with respect to the shock generally creates a favorable condition for Fermi acceleration only on one side. It is most often the dawn side that is favorable (Hess, 1968). This mechanism has not been compared with observations.
DIRECT PARTICLE ACCESS

The second major approach to answering the energy transport question is that of the direct access of interplanetary particles into the magnetosphere. Penetration of magnetosheath particles at the polar cusps has been observed (Frank, 1971). The helium content was first used to identify the plasma as coming from the solar wind. Russel et al., (1971) observed penetration of magnetosheath-like spectra at the polar cusp during a magnetic storm.

Hones (1972a) (also Akasofu, et al., 1973) reported a boundary layer in the geomagnetic tail containing protons of lower velocity and number density than in the magnetosheath, but having a similar spectrum. This boundary layer was observed to be thicker (~1 \( R_e \)) above and below the mid-plane of the tail. At the flanks of the mid-plane it was observed to be several 100 km thick if observed at all. It possibly extends completely around the tail. Hones suggests that this anti-sunward flow of plasma is along field lines connecting to the polar cusps. Regardless of the model, the boundary layer appears to be magnetosheath particles having direct access to the tail.

Hill (1973) has proposed a model which allows direct particle access in a broad region on the front side of the magnetosphere rather than only at the cusps. Hill's mechanism is based on Alfvén's current model of a magnetic neutral sheet. For parallel fields at the boundary plasma flows across the boundary to the region of smallest particle density with respect to field density. For antiparallel fields, particles flow to the boundary from both sides and move along the boundary (Alfvén, 1971).
Another observation of magnetosheath plasma in the tail occurred after the onset of a magnetic storm. A burst of plasma was observed to flow down the tail (Garrett, et al., 1971). A magnetosheath-like spectrum is seen along with a plasma sheet spectrum in this flow. This flow does suggest the entry of sheath particles in the region of the earth rather than at the tail.

The inverse process of plasma sheet particles escaping into the magnetosheath has also been reported (Hones, 1972b). Fluxes of 10-30 kev protons are seen in the sheath during substorms. A satellite monitoring the solar wind showed that they did not originate outside of the bow shock.

Experimental evidence has confirmed the flow of sheath particles into the magnetosphere. Magnetosheath particles have been shown to be a component of the plasma sheet. Sheath particles are also related to another feature of the tail, the boundary layer. These two observations support concepts of direct particle access.

1.4 RESEARCH OBJECTIVES

This thesis presents particle data from the magnetosheath at a distance of 60 R_e. The observed velocity distribution function is determined from the data for twenty minute (~1000 km) averages in the sheath. A study of the general structure of the bulk flow parameters across the sheath is performed for 10 lunations of data. The characteristics of the inbound and outbound sheaths are compared.
The energy transport problem is examined using both approaches. Turbulence in the sheath is measured by the shape of the distribution function. The ratio of energy in the tail to that in the main peak is used to indicate a high energy tail or diffusion in velocity space. This technique is described in Chapter 3. Turbulence, which is known to correlate to interplanetary conditions, is studied in relation to geomagnetic conditions.

The geomagnetic tail is observed for evidence of magneto-sheath particles having direct access to the tail. The detectors are oriented to center on an anti-solar flow and to give a measure of the isotropy of the particles. The moon does not always pass through the plasma sheet, but it observes tail phenomena at various latitudes.

The particle distribution function itself is of interest. Perhaps the behavior of the distribution function will give some indication of the mechanism producing it.

The purpose of this thesis is to examine the role of the magnetosheath in the dynamic earth-sun interaction by:

1) examining the structure of the sheath at 60 R_e, comparing the dawn and dusk sides.
2) comparing magnetosheath turbulence to geomagnetic activity
3) looking for magnetosheath particles in the tail
CHAPTER II

EXPERIMENT

The Suprathermal Ion Detector Experiment (SIDE) was deployed on the lunar surface as a part of three Apollo Lunar Surface Experiment Packages (ALSEP), in the Apollo 12, 14, and 15 missions. Physically the SIDE is a small package 9.1 kg in weight which stands 45 cm or about 18 inches tall on the lunar surface (Figure 2.1). The experiment was designed with the following objectives:

1) to study gases in the lunar environment, both indigenous and transient,

2) to observe the magnetotail and magnetosheath as the Moon passes through the Earth's magnetic tail,

3) to provide information on the plasma interaction of the solar wind with the Moon,

4) and to evaluate the electric potential of the Moon's surface.

2.1 INSTRUMENT DESIGN

The instrument consists of two detectors side by side, the total ion detector (TID) and the mass analyzer (MA) (Figure 2.2). Both detectors employ curved plate analyzers to measure the energies of incoming charged particles.

A schematic of the TID curved plate analyzer is shown in Figure 2.3. A flight path is defined by parallel cylindrical plates (127° 17' arc) having a potential V across them. Only
Figure 2.1  Apollo 12 and 14 SIDEs are shown in their deployed configuration on the lunar surface. Apollo 15 is shown in the laboratory in its deployment configuration (after Medrano, 1973).

Figure 2.2  A cutaway drawing showing the interior of the suprathermal ion detector experiment (after Freeman et al., 1970).

Figure 2.3  Diagram of the flight tunnel of the total ion detector (after Shane, 1969). The X axis is the look direction of the detector.
INTERNAL DIAGRAM OF THE
SUPRATHERMAL ION DETECTOR EXPERIMENT

FIGURE 2.2
\[ x_1 = 3.0 \text{ cm} \]
\[ x_2 = 3.0 \text{ cm} \]
\[ x_3 = 1.0 \text{ cm} \]
\[ x_4 = 1.0 \text{ cm} \]
\[ y_1, y_2, y_3, y_4, y_5 = 0.2 \text{ cm} \]
\[ y_6 = 0.5 \text{ cm} \]
\[ z_1 = 0.8 \text{ cm} \]
\[ r_2 = 4.25 \text{ cm} \]
\[ r_1 = 3.75 \text{ cm} \]

FIGURE 2.3
the charged particle whose centrifugal force along the curved path exactly balances the electrical force of the field of the plates will successfully exit through the slits at the end of the flight path. The force balance equation is

\[ \frac{mv^2}{R} = q \frac{V}{R \ln(r_2/r_1)} \]

where \( V \) is the voltage on the plates of radius \( r_2 \) and \( r_1 \) which define a flight path of radius \( R \) for a particle of mass \( m \), velocity \( v \) and charge \( q \). Energy per unit charge (\( \frac{1}{2} mv^2/q \)) is the quantity measured as a function of the voltage on the curved plates. The entrance slits and baffling define an acceptance cone for incoming particles approximately 6° in diameter which is equivalent to .0086 steradians.

The Mass Analyzer has a Wien velocity filter (\( \mathbf{E} \times \mathbf{B} \) field) in front of the curved plates to select a velocity \( V_o = E/B \). A mass range is defined (\( m = \frac{2E_o}{V_o^2} \)) by scanning both energy \( (E_o) \) and velocity \( (V_o) \). The mass analyzer is also known as the low energy detector since it cycles through six energy steps from .2 eV to 48.6 eV while the Total Ion Detector cycles through 20 steps defining energy channels centered on 10 eV, 20 eV, 30 eV, 50 eV, 70 eV, 100 eV, 250 eV, 500 eV, 750 eV, 1000 eV, 1250 eV, 1500 eV, 1750 eV, 2000 eV, 2250 eV, 2500 eV, 2750 eV, 3000 eV, 3250 eV and 3500 eV.

A Bendix 4028 Channeltron® using an 840° helix is the counting device used to collect the particles at the end of the flight path of each curved plate analyzer. The channel electron
multiplier operates in the pulse saturated mode so that the response is independent of the energy of the incoming particle. After the original energy of the particle has been measured the particle encounters a voltage of -3500 v along its flight path to the Channeltron®. This post acceleration considerably enhances the collection efficiency and thus the sensitivity of the instrument.

The lifetime of such a Channeltron® is important in space experiments. Figure 2.4 shows the electron gain of the channeltron as a function of its lifetime given in total accumulated counts. Each TID Channeltron® acquired approximately $3 \times 10^8$ counts during the pre-mission calibration procedures. Apollo 14 TID accumulated as estimated $1 \times 10^9$ counts by the end of 1972. Apollo 15 is estimated to have accumulated a maximum of $3 \times 10^9$ counts by the end of 1972. Apollo 12 would have a much lower accumulation of counts since for thermal control it was cycled to full operation for only 2 out of every 24 hours during the magnetosheath high counting rates. For the data presented in this thesis all three instruments should be well within the optimum operation range of their Channeltrons®.

Two other design problems have been considered: The effective rejection of electrons and prevention of contamination by solar ultraviolet photons. Tests were made on a back-up model of the instrument to show that neither electrons nor solar ultraviolet photons have a significant effect on the response of the SIDE. A 25 kev beam of $2.1 \times 10^8$ electrons/cm² sec caused the background counting rate in the test chamber to rise
Figure 2.4  The lifetime of a channel electron multiplier operating in a pulse saturated mode in terms of total accumulated counts (after Schmidt, 1969).
from 4 counts/sec to 13 counts/sec. This is a representative solar wind flux which is much more energetic than solar wind. It was assumed that less energetic particles would not have any different effect. A flux of $4 \times 10^{12}$ photons/cm$^2$/sec caused the background to rise from 5 counts/sec to 13 counts/sec. The experimental beam was directed straight into the instrument, however, the instrument never points at the sun directly. All surfaces including the entrance, exit and baffling slits are gold plated and platinum blacked to minimize UV scattering.

One other important feature of the SIDE is the ground plane stepper (Figure 2.5). A wire mesh in contact with the lunar surface is connected through a voltage supply to a grid above the entrance aperture of the detector. We assume that the umbrella-like mesh is in good electrical contact with the lunar surface at a potential $\phi_o$. The stepping voltage supply establishes a voltage difference of $\phi_t$ between the ground plane mesh and the grid at the top of the instrument. Consequently, the potential seen by an ion just above the entrance aperture is $\phi_t + \phi_o$. The stepping supply completes one cycle in 61.2 minutes changing the voltage ($\phi_t$) from -27.6 to +27.6 in 24 steps.

The case of specific interest is that of a small surface potential of a few volts positive. Positive thermal ions in the lunar atmosphere would be repelled from reaching the surface or the instrument. Ions may be accelerated into the lowest energy channel (10 eV) of the TID if the sum $\phi_t + \phi_o$ is as large as -10 volts. The surface potential $\phi_o$ can be
Figure 2.5

The Suprathermal Ion Detector Experiment (a) as deployed on the lunar surface, and (b) showing the ground plane and top wire grid configuration schematically. Thermal ions are attracted to or repelled from the top of the instrument by the top grid. $\xi_T$ is the voltage produced by the stepping supply. The ground plane is in actual contact with the lunar surface (after Fenner et al., 1973).
inferred from the stepper voltage $\phi_t$ required to observe accelerated ions in the low energy channels. They are observed at energy $E$ given by

$$E = E_i - (\phi_t + \phi_o)q$$

It is assumed that the thermal atmospheric ions have an initial energy $E_i = 0$. The instrument was designed to measure thermal ions in the presence of a surface potential and thus determine the value of that potential.

2.2 CALIBRATION

The SIDE was calibrated in the laboratory to relate the instruments' counting rate to the measured fluxes. Figure 2.6a depicts a single ray of particles incident on the detector. The response $R_1(x_1, x_2)$ of the detector is dependent on the position $(x_1, x_2)$ that the particle crosses the aperture. The angular dependence $R_2(\theta, \phi)$ is the response to the incident angle with respect to the detector normal. Each energy channel must be calibrated to measure its $R_1$ and $R_2$, but there is still a response due to energy $R_3(E_i)$ for a single channel $E$. The efficiency of the detector ($\epsilon$) is the ratio of the channeltron counting rate to the number of incoming particles at energy $E_o$, incident on the aperture at $x_1 = x_2 = 0 = \theta = \phi$. The product of all these factors, the total transmission function ($T$), is pictured in only 2 or its 5 dimensions in Figure 2.6b. It relates the counting rate (CR) to the measured differential flux ($j$).
Calculation of the geometric factor of the SIDE includes (a) a consideration of a ray of particles incident on the detector's entrance surface at a position $X_1$, $X_2$ with a incident angle defined by $\theta$ and $\phi$, having an energy $E_i$. (b) a consideration of a transmission function depending on the 5 parameters shown in part (a), only 2 of which are plotted here, and (c) an approximation of this transmission function by a box function, i.e. using a step function for the dependence of each of the parameters.
FIGURE 2.6
\[ T(x_1, x_2, \theta, \phi, E_i) = R_1(x_1, x_2) \, R_2(\theta, \phi) \, R_3(E_i) \quad (2.1) \]

\[ \text{CR}(E) = \int \! \! dx_1 \, \int \! \! dx_2 \, \int \! \! d\theta \, \int \! \! d\phi \, \int \! \! dE_i \, T(x_1, x_2, \theta, \phi, E_i, E) \, \epsilon(E) \, j(E) \quad (2.2) \]

Physically measuring a five variable transmission function is a formidable task. A very useful simplification of this procedure uses a parallel beam covering the entire entrance aperture uniformly. The parallel beam geometric factor \( G_0 \) is determined by

\[ \text{CR}(E) = G_0(E) \, j(E) \]

and \[ G_0(E) = R_1(x_1, x_2) \, \epsilon(E) \]

\( R_1(x_1, x_2) \) will have the units of area and may be considered as a box function indicating an effective area (\( A(E) \)). Still using a parallel beam and varying its angle with respect to the detector normal the angular response function may be determined. Two such measurements \( R(\theta, 0) \) and \( R(0, \phi) \) are shown in Figure 2.7. Using the FWHM of these measurements and assuming cylindrical symmetry an effective solid angle \( \Omega(E) \) may be calculated. An independent calculation assumes a cone of 3° radius as an approximation to the solid angle defined by the geometry of the slits to calculate an effective solid angle \( \Omega(E) = .0086 \) steradians, in agreement with the measured response functions.

Each of the functions in equation 2.1 has been simplified to a box function except \( R_3(E_i) \). A monoenergetic (±2eV) parallel beam at \( \theta = \phi = 0 \) is used to measure the energy response (Figure 2.8). The FWHM is designated the passband width
Figure 2.7  Functions $f(\theta, 0)$ and $f(0, \phi)$ are plotted versus the beam angle from maximum response for a typical TID channel. The direction of maximum response varied from 0 to $3^\circ$ from the detector look direction for the various energy channels (after Lindeman, 1973).

Figure 2.8  The energy response of the SIDE for a typical calibration run using a single energy channel (after Fenner, 1971).
APOLLO 14 TID
50 eV/q

RELATIVE RESPONSE

BEAM ANGLE FROM MAX. RESPONSE

---R(θ, α)
---R(0, φ)

FIGURE 2.7
ENERGY RESPONSE
SIDE FRAME No. 11

FIGURE 2.8
$\Delta E$ of channel $E$, converting $R_3(E_i)$ to a box function. In this data analysis $\Delta E$ was averaged for all the channels and a uniform value $\Delta E = E/10$ was used.

The total transmission function (Figure 2.6b) has now been approximated by box functions as illustrated in Figure 2.6c. For the case of a differential directional flux equation 2.2 has become

$$CR(E) = A(E) \, \Omega(E) \, \epsilon(E) \, j(E) \, \Delta E$$

$$G = A(E) \, \Omega(E) \, \epsilon(E)$$

For this data analysis $G = 10^{-4}$ cm$^2$ ster was used for all three instruments and all channels. The tolerance in this value is approximately ±70% (Lindeman, 1973).

2.3 DATA HANDLING

One SIDE frame (1.208 sec) is the time required for a single energy or mass step and 1.13±.025 sec of that time is used for ion data accumulation. A TID energy spectrum consists of 20 SIDE frames. A SIDE cycle is composed of 6 TID energy spectra (120 SIDE frames), 2 more frames used to measure the background (i.e. the curved plates grounded), and 6 frames using known frequency oscillators to check the counting electronics. A ground plane stepping cycle consists of 24 SIDE cycles. The above description is the normal mode of operation. Although several other modes are available by real time commands the normal mode was used in all the data processed for this paper.
There is no data storage or memory facility in the instrument. All data is telemetered real time to the tracking stations. Besides the counting rates for both detectors, the voltages on the curved plates, channeltron, stepper, and temperatures of 6 sensors and several other parameters are transmitted as housekeeping data. These data tapes from the tracking stations are sent to Houston where they are edited for synchronization and parity bit errors. The ALSEP experiments are sorted and the SIDE data are compressed to form the NPAK tapes received at Rice. (The format of NPAK is given in Appendix A.1) The EDIT program used to process this data (Appendix A.2) checks the plate voltages, the mode register, a continuity word (indicating missing data) and parity words as a quality check on the data.

2.4 ORIENTATION IN SPACE

The locations of the 3 SIDE instruments on the Moon are shown in Figure 2.9. At the time of deployment each of the instruments was leveled to 5° accuracy by the astronauts using a bubble level on the top of the case. The instrument is built with a 15° angle between the detector normal and the normal to the top of the case. The Apollo 12 instrument was placed so that the detector looked 15° due west. The Apollo 14 instrument, 6° away in longitude from Apollo 12 ALSEP was placed in the opposite orientation so that the 14 detector looks 15° due east. There is a total of 36° difference in the look
Figure 2.9

A map of the moon shows the location of the three SIDE instruments which were deployed in the Apollo 12, 14 and 15 ALSEP packages. The latitude and longitude of the three sites are listed. The values of the magnetic field at the three sites is from Dyal et al., 1972.
FIGURE 2.9

|        | LONG.  | LAT.  | $B_x$ (up) | $B_y$ (east) | $B_z$ (north) | $|B_i|$ |
|--------|--------|-------|------------|--------------|---------------|--------|
| APOLLO 12 | 23.5 W | 3.0 S | -244±2     | -130±18      | -256±8        | 38±3   |
| APOLLO 14 | 17.5 W | 3.7 S | -93±4      | +38±5        | -24±8         | 103±5  |
| APOLLO 15 | 3.6 E  | 26.4 N| +4±4       | +1±3         | +4±3          | 6±4    |
directions of the Apollo 12 and Apollo 14 detectors. The Apollo 15 instrument is 20° east of Apollo 14 ALSEP and the detector tilt has the same east-west orientation as 14. The total difference in the look angles of Apollo 14 and 15 is simply the 20° due to longitude. Apollo 12 and 14 instruments are 3° and 4° from the lunar equator and consequently look almost parallel to the lunar equator. The 26° latitude of the Apollo 15 instrument was compensated by an extra leg on the side (see Figure 2.1), to tilt it back into a plane parallel to the lunar equator. The Moon's equator varies as much as 1½° away from the solar ecliptic plane. All 3 detectors look essentially in the solar ecliptic plane with a maximum deviation of 9°. Figure 2.10 shows the Moon's orbit projected onto the plane of the ecliptic. The detector look directions are shown in relation to the bow shock and the magnetopause of the Earth's magnetic tail. The experiment was designed so that Apollo 15 looks directly into the magnetosheath on the inbound (dusk) side, Apollo 12 looks directly into the sheath on the outbound (dawn) side and Apollo 14 looks directly up the magnetotail towards the earth. The rotation of the detector look angles in the solar ecliptic due to the Moon's spin and orbital motion is plotted on Figure 2.11 as a function of the Moon's position in solar magnetospheric coordinates. Also shown on this plot is the angle of flow of magnetospheric plasma as a function of orbital position in SMLOA. This assumes a laminar flow model where the flow is parallel to the boundaries at the boundary crossings. The rotation of the flow direction as the Moon crosses the magnetosheath is in the
Figure 2.10

The look directions of the three detectors are shown at various locations in the lunar orbit. The average position of the bow shock and magnetopause are plotted from Explorer data (Behannon, 1968).

Figure 2.11

The detector look angles of all three instruments are plotted versus Solar Magnetospheric Longitude of ALSEP (SMLOA) for the dusk and dawn magnetosheath crossings. This geocentric coordinate system has its X axis pointing to the sun and its Y axis perpendicular to both the earth's dipole and the X axis. The Z axis is in the same sense as the north magnetic pole and is in the plane of the X axis and the dipole. This system reduces the motion of the dipole to the X-Z plane by definition. Thus it is useful to follow magnetospheric phenomena.
The angle of flow was calculated using the equations for laminar flow given in Howe, 1971. For the angle at the magnetopause

\[ \theta = \cot^{-1}\left[ \frac{b}{2a} \left( \frac{1}{1 + \frac{10-X}{a}} \right) \sqrt{\frac{1}{1 + \frac{10-X}{a}}} \right] \]

where \( a = 15.9 \, R_e \)
\( b = 23.9 \, R_e \)

at a position along the magnetopause having the value \( X \) for its \( X \) component in Solar Magnetospheric coordinates.

At the bow shock

\[ \theta = \cot^{-1}\left[ \frac{b}{a} \right]^2 \left( \frac{a+d-X}{y} \right) \]

where \( a = 177.7 \, R_e \)
\( b = 56.7 \, R_e \)
\( d = 13.5 \, R_e \)

at a position \( X \) along the bow shock.

The result of the changing angle of flow across the sheath and the changing look direction of the detector is an almost constant angle between the detector and sheath flow.
Boundaries shown are average values from Explorer data.

FIGURE 2.10
FIGURE 2.11
same sense as the rotation of the detector look directions as the Moon rotates on its axis. This results in a constant relationship between each detector normal and the angle of flow in the static theoretical magnetosheath.
CHAPTER III

DATA ANALYSIS PROCEDURE

3.1 DISTRIBUTION FUNCTION

As discussed in section 2.2, the SIDE is designed to measure directional differential flux \( j(E) \) in particles/cm\(^2\) ster sec ev. This is related to the total flux by an integration over energy and solid angle.

\[
F = \int \int j(E) \ dE \ d\Omega
\]  \hspace{1cm} (3.1)

Another representation for the same flux may be given in velocity phase space.

\[
F = \int \int f(\vec{v}) \ v \ d^3 v
\]  \hspace{1cm} (3.2)

where \( f(\vec{v}) \) is the particle distribution function or the number of particles described by velocity \( \vec{v} \). The total flux is obtained by an integration over velocity space. The unit volume \( d^3 v \) transformed to spherical coordinates becomes \( v^2 \ dv \ d\Omega \). Substituting this expression for the unit volume and converting from velocity to energy dependence using the simple relation \( E = \frac{1}{2} m v^2 \), Equation 3.2 becomes

\[
F = \int \int f(E) \ \frac{2E}{m^2} \ dE \ d\Omega
\]  \hspace{1cm} (3.3)

comparing equations (3.1) and (3.3) the differential flux and distribution function are related by

\[ j(E) = f(E) \ \frac{2E}{m^2} \]
Therefore the distribution function of particles may be
determined from the measurements of the differential flux.

A physical description of a plasma such as the solar wind
or the magnetosheath would catalog the position and velocity
of each particle at each time t. Such a description is
characterized by the particle distribution function
\( f(x_1, x_2, x_3, v_1, v_2, v_3, t) \) which we now can derive from the measured
differential fluxes.

There are two methods of obtaining a macroscopic descrip-
tion of the plasma from this microscopic one (the distribution
function). First, by taking the moments of the distribution
function, hydrodynamic plasma parameters may be estimated:

\[
\begin{align*}
\text{Number density} & \quad N = \int f(\vec{v}) d^3v \\
\text{Bulk velocity} & \quad V_B = \frac{\int f(\vec{v}) \vec{v} d^3v}{N} \\
\text{Thermal speed} & \quad W^2 = \frac{\int f(v) (v - V_B)^2 d^3v}{N}
\end{align*}
\]  

(3.4)  
(3.5)  
(3.6)  

\( kT = \frac{1}{2} m W^2 \), \( k \) = Boltzmann's constant \( m \) = proton mass,
\( T \) = temperature, \( V_B \) = bulk velocity.

This procedure, known as the method of moments allows a descrip-
tion of plasma behavior directly from the observed distribution
function.

The second method involves fitting the data points \( f(\vec{v}_i) \) to
a model distribution function. The convected Maxwellian from
classical thermodynamic gas theory is commonly used:

\[
f(\vec{v}) = N \left( \frac{m}{2\pi kT} \right)^{3/2} \exp \left[ -\frac{m (\vec{v} - \vec{V}_B)^2}{2kT} \right]
\]  

(3.7)
This is quite adequate in describing the solar wind. The magnetosheath differs from this description at times because of an enhancement of particles at high velocities. A mathematical adaption of this model (done by Olbert for electron spectra, Olbert 1969) provides for this enhancement or high energy tail. It is known as the Kappa ($\kappa$) distribution and it reduces to the Maxwellian as $\kappa$ goes to infinity:

$$f(v) = \frac{N}{\pi^{3/2}w^{3}}\frac{\Gamma(\kappa+1)}{\Gamma(\kappa^{3/2})\left[1 + \frac{(v - V_{B})^{2}}{w^{2}}\right]^{\kappa+1}}$$

$$kT = \frac{1}{3}mW^{2}(\kappa/(\kappa-3/2))$$

By varying $\kappa$ this distribution function gives an adequate description of magnetosheath data.

3.2 FITTING PROCEDURE

A combination of both the method of moments and the method of fitting to a model distribution function was used to examine the individual sheath spectra. A least squares curve fit would be the optimum treatment, but the computer time required is formidable for even a single magnetosheath crossing. Consequently a compromise was arranged to estimate the parameters $V_{B}$ and $T$ directly from the data points using the method of moments. Medrano (1973) has shown this to be a very good description of the main peak (5 points) of the distribution. Then use these parameters in a simple fit to the Kappa distribution, varying $\kappa$ to describe the tail. The calculated model distribution function is normalized to the data points to obtain the number density. The angle $\theta$ between the detector
and the flow was assumed to be $0^\circ$ for these calculations.

Figure 3.1 shows the Kappa distribution plotted for three values of $\kappa$ using the temperature ($T=9.51 \times 10^5$ K) derived from the variance of 5 data points about the mean (second moment). Simply choosing the best $\kappa$ is not adequate because now points around 500 km/sec do not fit the distribution. This plot suggests that a higher temperature is needed to fit these points. A subroutine was added to calculate the temperature needed to fit the 3rd data point from the peak. Then using this temperature an iterative routine chose the necessary $\kappa$ to fit the 3rd to the last data point in the tail. The results shown in figure 3.2 found $T=10.46 \times 10^5$ K and $\kappa=3.28$. Note also that for the higher temperature the tail fit is less sensitive to $\kappa$.

Many spectra are more complex than a single peak that can be fit by a Kappa distribution. A multiple peaked treatment was developed that used the parameter estimates, as before, to fit the main peak. The calculated function was then subtracted from the data and the residue was used for parameter estimates to fit the second peak and so on. Figure 3.3 illustrates this procedure using Maxwellian distribution functions. A much better fit is obtained using Kappa distributions as seen in figure 3.4 for the same data. The multiple treatment can be a very useful tool, however, it is extremely difficult to allow the program to decide whether or not it is a necessary procedure. Some spectra should not be fit in this way, although it is mathematically possible, because they seem to be varying on a time scale less
Figure 3.1  Plots of the Kappa distribution function are shown. SIDE data points are indicated by circles. Error bars are given for each data point.

Plots for 3 values of $\kappa$ are shown. All have the value $T = 9.51 \times 10^5 \circ K$.

Figure 3.2  A second temperature estimate ($T = 10.46 \times 10^5 \circ K$) is used in the Kappa distribution function. Plots are made for two values of $\kappa$. $\kappa = 3.28$ shows the best fit to the data points.

Figure 3.3  The procedure for fitting multiple peaks is illustrated using a Maxwellian distribution function to fit both peaks.

Figure 3.4  The same procedure for fitting multiple peaks is shown using a Kappa distribution function for both peaks.
DAY 88
1318 UT

LOG IONS / M^3/(M/SEC)^3/STER

V (km/sec)

FIGURE 3.4
than the 24 sec accumulation time for a single spectrum and thus are not valid spectra.

It is at this point in the data analysis that we attempt to find the appropriate time scale to study events in the sheath. The fitting program was arranged to average over a variable number of spectra. The same data were then processed averaging over 1, 6, and 24 spectra (figures 3.5, 3.6) indicating time scales of 24 sec, 2.4 minutes, and 9.6 minutes respectively. Plots in which the data points are not connected indicate that the maximum counting rate was in the E<sub>1000ev</sub> channel or lower. In this case the data were not fit to the model distribution function. From these figures the data appear to be more stable the longer the average. 48 spectra or 19.2 min averages seemed optimum for the bulk processing of sheath crossings to show the macroscopic structure of the plasma parameters, and yet not to average out gross temporal variations.

3.3 WAVE ANALYSIS

In order to understand the magnetohydrodynamic processes in the sheath it is desirable to study the turbulence in the sheath and the type of waves present. Magnetometer experiments (Kaufman 1970) have used a wave oriented coordinate system with parameters B<sub>k</sub>, B<sub>1</sub>, B<sub>m</sub> which are able to separate the wave types. By running a power spectral density analysis on these variables the power in each type of wave may be determined. It is reasonable then to ask if a similar separation of particle parameters can
Figure 3.5

Nine consecutive 24 second SIDE spectra are plotted. They are labeled with the start time of a SIDE cycle which contains 6 spectra. Error bars are shown with the data points. A curve through the data points is the best fit of a Kappa distribution function to the data. The absence of a curve indicates the program did not fit the data to a Kappa distribution function either because the peak of $F(v)$ was in a channel $\leq 100$ eV or the data was too random. All of the data shown are for day 88, 1972.

Figure 3.6

The first two columns show data averaged over one SIDE cycle or 6 individual spectra. The first 6 spectra in the previous figure are averaged to give the second averaged spectrum in this figure, labeled 0610 UT. The last column shows data averaged over 4 SIDE cycles. The first 4 averaged spectra in this figure are again averaged to give the first spectrum in this column, labeled 0608 UT.
separate the wave types, using only particle data.

Alfvén waves are not detectable by particle data alone since they involve the rotation of the direction of the transverse magnetic field component. The magnitude of the field is constant as is the particle pressure and number density. Magnetosonic and sound waves involve fluctuations of particle pressure and number density, but there is no simple separation of the two using only particle data.

Solar wind particle experiments have shown results of power spectral density studies of particle number density. Most of these studies (Intriligator, 1970) are in the frequency range of $10^{-3}$ to $10^{-4}$ Hz, requiring data segments from several hours to a day. The moon is not in the magnetosheath long enough to measure frequencies of this order of magnitude and not include spacial effects. The results of most power spectral studies using either particle or field data show flat spectra indicating a degree of turbulence over a region of frequencies rather than peaks indicating waves at a certain frequency.

The program used to do a power spectral density analysis on SIDE data is given in APPENDIX A.3. It assumes that the spectra are taken at equal intervals, i.e. it ignores the calibration cycle and divides the time of a SIDE cycle equally by the 6 spectra. It also removes any macroscopic structure in the data by taking a running average and looking at oscillations about that average. The Fourier transform of the autocorrelation
coefficient was used rather than the fast Fourier transform. Its efficiency was adequate for small segments of data or higher frequency regions. Figure 3.7 shows a typical plot of power spectral density in the sheath near the magnetopause. Integral flux was used as the variable. It reflects the number density if the velocity is assumed to be constant over the four hour period of data.

This method of analysis does not seem to hold a great deal of information for SIDE data, since the frequency range is limited on one end by the Nyquist frequency (0.02 Hz) and on the other by the amount of continuous data in the sheath not reflecting spatial effects (~0.001 Hz). Also specific wave information is not available.

Another method of analyzing the turbulence is based on the consideration of the wave particle interactions. The distribution function itself is influenced by the waves and the degree of turbulence in the plasma. As the waves dump energy into the particles the distribution of velocities spreads out. A new parameter discussed in section 3.4, is used to indicate the degree of turbulence in the distribution function. It is constructed by dividing the energy spectrum in half at 1250 eV, which is greater than the main magnetosheath flow energy (250 - 750 eV). The ratio of energy density in the second half of the spectrum with respect to the first half (containing the main peak) is plotted to show the extent of diffusion of particle velocities. Many sources of turbulence would produce high energy particles. These appear as secondary
Figure 3.7

Plot of the power spectral density calculated from a segment of data ~2 hours long. Lag numbers convert to frequencies as indicated by the arrows above the data.
DAY 279 (1971)
17:10:52-19:53:00
(63 SIDE Cycles)

POWER SPECTRAL DENSITY
\([\text{ion/cm}^3\)]^2/\text{Hz}\]

Lag Number

0.2 Hz

0.004 Hz

0.001 Hz

FIGURE 3.7
peaks in the 24 second spectra, but when the data are averaged they contribute to an enhanced high energy tail, which is reflected by the energy density ratio. This parameter will be discussed further in the next section.

3.4 PARAMETER STUDY

Besides the fitting procedure, bulk processing of the SIDE data includes a plot of the following key parameters: pressure (dynes/cm²), energy density ratio, temperature (10⁵°K), main flow velocity (km/sec) and number density (ions/cm²). The computer program is given in Appendix A.4. The counting rates are converted to points in a measured velocity distribution function. Using equation 3.5 and converting the integral to a finite sum, the bulk velocity is calculated to be:

\[ V_B = \frac{\sum f(v_i) v_i (v_{i+1} - v_{i-1})/2}{\sum f(v_i) (v_{i+1} - v_{i-1})/2} \]

Likewise, using equation 3.6 the thermal speed is calculated:

\[ T = \frac{m}{2k} \frac{\sum f(v_i) (v_i - V_B)^2 (v_{i+1} - v_{i-1})/2}{\sum f(v_i) (v_{i+1} - v_{i-1})/2} \]

These two values are substituted into the expression for the model distribution function. It is normalized to the maximum flux, and this normalization is used to calculate the number density. The pressure is derived from the density (n) and temperature (T) as

\[ P = nkT \]
where $k$ is Boltzmann's constant. To these familiar parameters was added the ratio of the energy density of the second part of the spectrum to that of the first part. Figure 3.8 illustrates this new parameter by plotting the pressure, which is dependent on the main peak, and the total energy density of the spectrum, which closely follows the pressure. Then the energy density of only the upper part ($> 1250$ eV) of the spectrum is plotted which follows the same general upward trend as the total energy density. In fact, to convert pressure to total energy density an empirical factor of three may be used. The last line is a plot of the ratio of the 3rd line to the 2nd, i.e. The ratio of energy density for $E > 1250$ eV to energy density for $E > 100$ eV or total energy density of the spectrum. Notice that this ratio is generally a constant although pressure is increasing as well as total energy density. This indicates that the character of the spectrum is the same although number density is increasing.

The choice of 1250 eV as the break point to calculate the energy density ratio of the high energy particles to the total spectrum was an arbitrary one. However, it is adequate for the velocities observed in the sheath. Figure 3.9 illustrates the fluctuation of the ratio for different bulk velocities. The product of $v^3$ and $F(v)$ is plotted for three distributions functions having $V_B = 300, 400$ and $500$ km/sec. The area under these curves represents energy density. For a change in bulk velocity from $300$ km/sec to $400$ km/sec the energy density ratio of a kappa = 2 distribution function changes from 1% to 10%. Only for $V_B > 400$ km/sec is the
Figure 3.8  
A parameter plot illustrates the new parameter Energy Density Ratio. Pressure (calculated from NkT) is plotted at the top. Energy density of the spectrum is calculated by the analytical sum $\sum E_i f(E_i) dE_i$ for energy channels $\geq 100$ eV. The next line is the same calculation of energy density for channels $> 1250$ eV. The ratio of the 3rd line to the 2nd is shown in the last line as the energy density ratio.

Figure 3.9  
In velocity space the expression for energy density becomes $\sum m v_i^2 f(v_i) dv_i$. Using a Kappa = 2 distribution function for $f(v)$, the quantity $v^2 f(v)$ is plotted for 3 different values of bulk flow velocity. For the 2 lower values, the shaded areas illustrate the energy density in the high energy region of the spectrum. The velocity corresponding to the 1250 eV energy channel was used as the break point in the spectrum.
FIGURE 3.8

1972 APOLLO 14
DAY 86 HR 13 MIN 49
$V^3 \times F(v) \left[2 \times 10^6\right]$ (ions/m$^3$)

500 km/sec

400 km/sec

300 km/sec

$T = 10^6$ K
$K = 2$
$N = 5$ ions/cm$^3$

FIGURE 3.9
energy density ratio significantly dependent on bulk velocity. Later in the summary plots (Figures 5.7) it will be seen that the bulk velocities measured were usually < 400 km/sec.

Figure 3.10 shows a three dimensional plot of each average spectrum of distribution function versus velocity. A uniform background counting rate averaging 10 counts per channel is shown by the heavy line at the first of the spectra. Note the change in the spectra shortly after 0000 UT on day 87 and after 1200 UT on day 88 are reflected by an increase in the ratio in Figure 3.8. Figure 3.11 shows the complete parameter study for this piece of data where the energy ratio is calculated even if the other parameters are not treated due to the absence of a valid spectrum. The first part of this plot is an inbound magnetosheath crossing. A magnetopause crossing is seen slightly before 2000 UT on day 87 and SIDE remains in the tail until around 500 UT on day 88 when it enters the sheath again for a short while.
Figure 3.10
The distribution function spectra calculated from the data are plotted in a 3-dimensional display, having the time of the observation as the 3rd axis. Note that the Y axis is logarithmic. In order to visualize the significance of these data a flat counting rate spectrum of 1 count in each energy channel was converted to a distribution function spectrum and plotted here as the heavy line at the beginning of the plot. Comparing this line to those after 2000 UT on day 87 identifies these data as being outside the sheath or showing the absence of a directed flow. The sheath is re-entered around 0600 UT on day 88 with strong peaks around 300 km/sec.

Figure 3.11
The macroscopic parameters calculated from the measured distribution function spectra are the following: pressure (dynes/cm²), energy density ratio (percent), temperature (10⁵ K), bulk flow velocity (km/sec), and number density (ions/cm³). Note that the pressure plot is logarithmic. A horizontal line (after 2000 UT, day 87) means that these parameters are not calculated in the absence of a directed flow.
1972 APOLLO 14
DAY 06   HR 14 MIN 2

FIGURE 3.10
CHAPTER IV

MAGNETOSHEATH OBSERVATIONS

SIDE data from November 1971 through August 1972 was processed to study general sheath structure. These 10 months are the first lunar orbits for which information from all 3 instruments is available during both sheath crossings. A measure of the total flux observed is used to describe the gross features of the data. A differential flux spectrum is obtained from the counting rates and then a Riemann sum of this spectrum is taken. The log of the integral flux is plotted versus time along the lunar orbit, showing data from the 3 instruments simultaneously. Figures 4.1-4.10 referred to as lunations 1 to 10 give these plots for the 10 lunar orbits treated. A 10 minute running average of the integral flux is used in order to smooth the data slightly.

4.1 MAGNETOSHEATH POSITION AND BOUNDARY CROSSINGS

Local sunrise (SR) and sunset (SS) are marked in the integral flux plots for each instrument. These have little or no physical relation to the position of the sheath, but are used to orient the location in the lunar orbit. The value of π in solar magnetospheric (SM) longitude is marked on the plots to study sheath position. This value is the center of the theoretical magnetotail. The theoretical magnetosheath might be expected to be symmetrical in SM coordinates about the longitude π for a single moment in time.
A logarithmic plot of the integral of the measured flux is shown for all three instruments. Times of local sunrise (SR) and sunset (SS) are marked for each ALSEP site. The value of π in Solar Magnetospheric coordinates is plotted as an indication of the expected location of the center of the tail. Bars above the X axis indicate periods of magnetosheath data. Special periods of low energy ion spectra are labeled as '100 eV'. Times of sudden impulses in the geomagnetic activity are indicated by 'SI' followed by the exact time. High energy particles ('h.e.') at the onset of the magnetosheath are indicated on one occasion. Periods of excessive transmission noise in the data are also labeled.
Remember that the data from a single orbit are taken over a period of two weeks. Consequently, temporal as well as spatial variations are involved. Significant events such as sudden impulses (SI) which are followed by a geomagnetic storm are labeled on the plots.

The most important factor in interpreting the sheath position in these data is the angle of the detector with respect to the expected flow direction. The flow of plasma inside the theoretical sheath is assumed to be parallel to the boundaries at the boundaries and varying gradually between them. See figure 2.11 for a plot of detector angles with respect to flow direction. At the bow shock the flow direction is expected to be 26° away from the aberrated solar wind direction (5.7° offset from the direction to the sun). This angular change is quite significant for a detector with a very narrow (6°=FWHM) response function. Apollo 14 and 15 instruments were arranged to favor the sheath flow direction on the inbound side and Apollo 12 and 14 instruments favor the sheath flow direction on the outbound side. The large deflection angle at the bow shock is observed as a sharp increase in the flux in the Apollo 14 and 15 instruments on the inbound side and in the Apollo 12 and 14 instruments on the outbound side. The appearance of sheath spectra in these detectors and the increase in their integral fluxes will be the criteria for determining a bow shock crossing.
The magnetopause is identified by the change in number density across its surface, rather than by an angular change. The angle of sheath flow is only 5° from the antisolar direction at the magnetopause. Since magnetometer data are not available, this boundary is determined by the disappearance of sheath spectra which is usually accompanied by a sharp decrease in integral flux. Consequently, regions of enhanced flux seen in figures 4.1-4.10 can be identified as the magnetosheath. Bars above the x axis indicate the magnetosheath.

Some special events are labeled in the plots where large fluxes are not sheath data. One case is 100 ev ion bursts which the digital data show to be clearly in the tail. These are identified on figures 4.3, 4.5, 4.6 and 4.9. Another case is that of extremely high fluxes which exhibit a flat spectrum, seen later in figure 4.17. These unusually high fluxes are seen at the beginning of the inbound sheath in Apollo 15 data in figures 4.3, 4.4, and 4.5. It appears as though the channeltron is saturated by the sheath fluxes and does not relax between energy measurements, producing a flat spectrum. Normal sheath spectra were resumed shortly in lunations 3 and 4. Apollo 15 continued to be noisy throughout the sheath in lunation 5. Perhaps the telemetry noise in the sheath in figures 4.6 and 4.7 is also associated with this problem. This noise is not to be confused with the very turbulent spectrum observed at the onset of the inbound sheath by both Apollo 14 and 15 in lunation 9. Such a distinction is not apparent from the integral flux plots, but are labeled there after studying the digital data.
On two occasions a sudden impulse occurred in geomagnetic data while the SIDE was in the tail. On both occasions the sheath was compressed in past the SIDE location. Figure 4.5 shows a sudden impulse at day 87, 1805 UT and inbound sheath fluxes return even slightly more intense. A sudden impulse (SI) in figure 4.6 at day 120, 0422 UT is accompanied by a compression of the outbound sheath in past the SIDE. These two events may also be interpreted as a flow of plasma in the tail, since magnetometer data is not available to identify the magnetopause. However, the sheath compression (Freeman, 1964; Burke et al., 1973) is a plausible explanation since the distribution function of particles in these regions is not unlike the associated sheath flow.

On one occasion a sudden impulse and the subsequent storm occurred as the moon was entering the inbound magnetosheath day 55, 0642 UT (figure 4.4). The following sheath was characterized in the digital data by a very broad distribution function having a high energy tail which gradually dissipated toward the magnetopause.

Because of the unfavorable look direction of the detector with respect to the sheath (figure 2.10) for Apollo 15 on the outbound side and for Apollo 12 on the inbound side the magnetosheath was not clearly defined in these cases. Apollo 15 (in the outbound sheath) and 12 (in the inbound sheath) make angles of 47° and 60° respectively with the sheath flow. Although sheath spectra are not observed the integral fluxes are slightly enhanced in these cases.

Using the criteria for defining the magnetosheath given in the discussion above, a summary plot of sheath
Figure 4.11  A summary of magnetosheath observations for ten lunations is plotted versus the Solar Magnetospheric Longitude of ALSEP (SMLOA). Multiple boundary crossings are indicated by the vertical lines. The empirical bow shock (BS) and magnetopause (MP) locations are from the results of Howe, 1971.
observations is given in figure 4.11. SM coordinates are used rather than time along the lunar orbit in order to emphasize the sheath location with respect to the earth's dipole field. The empirical magnetopause (MP) and bow shock (BS) locations from Howe, 1972 are plotted over the data. Notice that the boundaries have been observed as far as .2 radian or ~ 11 R_e inside the empirical magnetopause and as far as .2 radian or ~ 7 R_e outside the empirical bow shock. The two most notable deviations are explained by the presence of magnetic storms. The general trend of the deviations to fall to the left of the empirical boundaries can be explained by the aberation of the solar wind flow direction. This aberration was included in Howe's coordinate system, but has not been included here. This offset of ~ 5° would move the boundaries .1 radian to the left. It is important that the aberation of the solar wind direction is clearly exhibited by the data. When this correction is added to the expected boundary positions, the average location of the boundaries from SIDE data agree quite well with Howe's results.

4.2 Behavior of the Distribution Function Across the Sheath

The sheath crossing is studied in detail for each of the 10 lunations by choosing to display data from detector with the optimum look direction for each sheath crossing. The energy spectra are displayed using time as a third dimension. Time is equivalent to position along the lunar orbit.

LUNATION 1

Apollo 15 data are given in figures 4.12 to 4.15 to describe the inbound sheath. The bow shock crossing around
LUNATION 1: DUSK MAGNETOSHEATH

Figure 4.12 - 4.13  Apollo 15 distribution function spectra are plotted versus the observation. The hour (UT) is marked every 10 hours. The time at the bottom of the plot refers to the first frame of data used.

Figure 4.14 - 4.15  Plasma parameters calculated from the Apollo 15 data are plotted. Time is marked in the same way as the spectral plots.

Figure 4.16  Apollo 12 distribution function spectra are plotted for the time period shown in Figure 4.12.
1971 APOLLO 15
DAY 331 HR 0 MIN 0

FIGURE 4.12
1971 APOLLO 15
DAY 331  H 0  M 0  S 0

FIGURE 4.14
0000 UT on day 332 is clearly seen in figure 4.12. The data before this time show the low intensity random fluxes observed outside the sheath at an angle of about 30° with respect to the solar wind. Notice that random high energy fluxes build until they form the second peak of the double peaked spectrum seen at the shock crossing. Each spectrum is an average of 20 minutes of data, consequently the details of the crossing are not evident. However, it is a multiple crossing even on this scale. One more low intensity spectrum is observed after the first sheath spectrum. The next spectrum shows a different high energy peak (~ 800 km/sec) as well as the main magnetosheath peak.

A sharp decrease in intensity before 2100 UT on day 333 is seen in figure 4.13. The distribution function peaks around 100 km/sec after the decrease. This is interpreted as a magnetopause crossing rather than a deviation in flow direction because it is observed simultaneously by the Apollo 14 SIDE as a decrease of the same order of magnitude. Several more such crossings are seen in the remainder of the data in figure 4.13.

Figures 4.14 and 4.15 are plots of the parameters that are calculated from the spectra seen in the previous two figures. The horizontal lines in figure 4.14 before the bow shock crossing at about 0000 UT on day 332 indicate that the parameters are not calculated until a magnetosheath spectrum is present. The energy ratio as explained in chapter 3 is always calculated. At the bow shock we find that about 25% of the total energy is contained in the second part of
the spectrum (>1250eV or > 500 km/sec). Notice that the energy in this part of the spectrum decreases as the moon crosses the sheath and is at a value of ~ 10% of the total energy at the magnetopause. It is important to note that as the energy distribution changes across the sheath the temperature or the width of the bulk flow peak is almost constant at 5x10^5 K. The bulk flow velocity decreases from ~ 400 km/sec at the bow shock to ~ 250 km/sec at the magnetopause.

For comparison, the Apollo 12 data for the same period of time are presented in figure 4.16. Although no energy spectrum is apparent, a slight increase in total flux can be seen in figure 4.16 by observing the slope of the distribution function along the time axis. This agrees with the increase in integral flux seen in figure 4.1. In the absence of a definite energy spectrum, no parameters were calculated.

Apollo 14 data are presented in figures 4.17-4.20 to display the outbound sheath of lunation 1. The change in the appearance from the earlier Apollo 15 data is attributed to the larger angle between the flow direction and the detector. The lower number density also is a reflection of the larger angle. The spectrum appears to be quite broad and this is reflected by a large energy density ratio of 25-50%. It is important, however, that the temperature of the main peak is the same as in the Apollo 15 data from the inbound sheath.
LUNATION 1: DAWN SHEATH

Figure 4.17 - 4.18  Apollo 14 distribution function spectra are plotted.

Figure 4.19 - 4.20  Parameter plots are given for the Apollo 14 data.
1971 APOLLO 14
DAY 337 HR 6 MIN 2

FIGURE 4.17
1971 APOLLO 14
DAY 337 HR 6 MIN 2

FIGURE 4.19
LUNATION 2

The parameter plots from the inbound sheath of Apollo 15 are compared with those of Apollo 14 for this lunation (figure 4.21). The temperature is almost exactly the same for both instruments. The bulk velocity is the same until the last burst of sheath data before 1700 UT on day 363. At this time Apollo 15 shows ~ 400 km/sec and Apollo 14 shows ~ 330 km/sec. The Apollo 15 pressure is greater by an order of magnitude throughout the sheath. The energy density ratio is the same in the first part of the sheath. However, in the second part, the energy density ratio is about 10% greater for Apollo 14 than Apollo 15.

The outbound sheath is seen in figures 4.22-23 for Apollo 14. We can compare the inbound and the outbound sheath on the same instrument. The parameters are again the same as for the inbound sheath except for a much higher energy density ratio. The angles with respect to the expected sheath flow are 29° and 15° for the inbound and outbound sheaths, respectively, for Apollo 14. Therefore, a higher energy density ratio in the outbound sheath cannot be attributed to a larger angle from the flow direction as seen before. Therefore, it is reasonable to assume that the higher ratio infers greater turbulence in the outbound (dawn) sheath at this time.

LUNATION 3

Apollo 15 data for the inbound sheath again show the enhancement of the high energy part of the spectrum outside the bow shock around 200 UT on day 25 (figure 4.24). This plot also shows the flat spectrum at the bow shock which is
LUNATION 2

Figure 4.21

Plasma parameters calculated from Apollo 14 data are compared with those from Apollo 15 data for the dusk (inbound) Magnetosheath crossing.

Figure 4.22 - 4.23

Plasma parameters calculated from Apollo 14 data are given for the dawn (outbound) magnetosheath crossing.
FIGURE 4.22
Figure 4.24 - 4.25
Apollo 15 distribution function spectra from the dusk magnetosheath are plotted.

Figure 4.26
Apollo 14 distribution function spectra show the dusk magnetosheath magnetopause crossing, and low energy fluxes inside the tail.

Figure 4.27
Apollo 14 distribution function spectra show the magnetopause crossing into the dawn magnetosheath.
1972 APOLLO 15
DAY 26   HR 21 MIN 57

FIGURE 4.25
responsible for the sharp peak in the integral flux plot (figure 4.3). It lasts several hours before the normal sheath spectra are resumed. Multiple magnetopause crossings are seen in figure 4.25 around 1700 UT, day 27. Again low energy fluxes \( \sim 100 \) eV are seen in the tail. These particles appear to be more isotropic than sheath particles. At the time of this crossing Apollo 14 was looking 30° away from the expected flow direction and Apollo 15 only 10° away. The two detectors always remain 20° apart in their look directions. The low energy fluxes are seen in Apollo 14 (figure 4.26) for this same passage. They are an order of magnitude less intense, but not as distorted as the earlier sheath spectra. The low energy particles are observed by Apollo 14 sporadically through the tail and are seen again in figure 4.27 at the magnetopause crossing \( \sim 600 \) UT on day 32.

**LUNATION 4**

The low energy fluxes of lunation 3 are seen again in the tail passage of lunation 4, but appear most strikingly at the outbound magnetopause in the Apollo 14 data (figures 4.28-4.29). Magnetosheath spectra are first seen around 1600 UT on day 61 and last several hours. Then a very intense burst of low energy ions appeared for several hours in the absence of a magnetosheath spectrum. This was most probably a magnetopause crossing as the sheath moved out past the moon's orbit. The parameters for this sheath crossing are seen in figures 4.30 and 4.31. Notice that the low energy spectra do not appear on this plot since they were not considered valid sheath spectra. The energy density
ratio is particularly low at the onset of the magnetosheath. It noticeably increases (Figure 4.31) toward the bow shock. Pressure is fairly constant, while both temperature and bulk velocity increase toward the bow shock. Number density does not increase as might be expected. The Apollo 12 data that are available (see Figure 4.14) are presented to compare with the Apollo 14 continuous data. Notice that the Apollo 12 data (Figures 4.32-4.33) are plotted on a different time scale and it is averaged over only one SIDE cycle (~ 2.5 min.). Discontinuous pieces have been placed together for the sake of comparison with Apollo 14. The character of the spectra seem to change more in Apollo 12 (Figure 4.32) than in Apollo 14 (Figure 4.29) which appear very stable. Comparison of the parameter plots (Figures 4.31 and 4.33) suggests a reason for the difference. Temperature is constant in both. Velocity is increasing in both but more rapidly in Apollo 12, particularly in the third data segment of about 2 hours. The most apparent difference between the two plots is the sharp change in number density in Apollo 12, which is also reflected in the pressure calculations. During this sheath crossing Apollo 12 is looking 11° from the expected sheath flow direction and Apollo 14 is looking 25° away. The measured distribution function is known to be more sensitive to θ near θ = 0° (Figure 4.51). Consequently, the slight variation of the detection angle with respect to the flow as the moon crosses the sheath has a much more pronounced effect on the data from the instrument nearest to the flow direction. The same effect is seen in Figure 4.21 a and b where the Apollo 15 detector is
LUNATION 4

Figure 4.28 - 4.29 The tail passage, boundary layer and dawn magnetosheath crossing are seen in Apollo 14 distribution function spectra.

Figure 4.30 - 4.31 Plasma parameters calculated from the Apollo 14 data are plotted.

Figure 4.32 Apollo 12 distribution function spectra are plotted for the look periods in the dawn magnetosheath.

Figure 4.33 Plasma parameters calculated from the Apollo 12 data are plotted.
1972 APOLLO 14
DAY 60 HR 0 MIN 0

FIGURE 4.28
1972 APOLLO 14
DHY 62 HA 2 MIN 29

FIGURE 4.29
7° from the expected flow direction and Apollo 14 is 22° beyond that. At an angle of 30° with respect to the bulk flow direction a change of ±5° in the flow will only slightly alter the number density of the measured distribution function. Viewing the flow directly (θ = 0°) a change in the flow of ±5° significantly alters the number density measured.

When only Apollo 12 data at distant intervals was available in the sheath, it was thought that perhaps the differences in the spectra (figure 4.32) might indicate different regions in the sheath (Fenner, 1971). However, the continuous data now available indicates that this is an angular effect. The sudden changes in intensity discussed in the master's thesis may be due to temporal changes in the flow direction. No evidence has been found in the continuous sheath data for a region of high density in the sheath.

LUNATION 5

This orbit is of particular interest because of a magnetic storm that occurred after the passage through the inbound sheath and caused the sheath to move in past the moon's orbit again. The sudden impulse was shown in figure 4.5 and more sheath data follow it. The parameters for Apollo 14 data during the inbound sheath are show in figure 4.34. As the sheath backed across the moon, Apollo 14 recorded a gradual increase in all flow parameters. Velocity increased to about 350 km/sec, but not as high as 500 km/sec. A look at individual spectra reveals a change from a smooth Kappa distribution (figure 3.1) before the sudden impulse to a definite double peak (figure 3.4) in the reappearance of the sheath.
LUNATION 5

Figure 4.34  Plasma parameters calculated from Apollo 14 data during the entire dusk magnetosheath crossing are plotted. They show two distinct periods during which the sheath was re-entered after the first magnetopause crossing.

Figure 4.35  Distribution function spectra from the mid-part of the Apollo 14 parameter plots are shown.

Figure 4.36  Parameters from the curve fitting of the first part of the Apollo 14 dusk magnetosheath data are shown. The value of kappa ($\kappa$) used in the distribution function and the value of temperature given by the fit are plotted. The chi square is given as a measure of the goodness of fit of the model distribution function calculated from the estimated parameters to the measured distribution function. The energy ratio is calculated from the data points in the measured distribution function.
These spectra are 10 minute averages. In the second sheath passage, the high energy component is stable enough to show up as a secondary peak on a 10 min time scale, but successive spectra show the peak at differing energies. Finally, it melts into a broad high energy tail. The 20 minute average spectra seen in figure 4.35 show the narrow spectra at 0600 UT day 88 with slight secondary peaks growing into broad spectra near 1600 UT. The change may be attributed to a change in flow direction. However, the multiple peaked spectra have often been associated with bow shock crossings (Fenner, 1971). Their presence is reflected in the increase in energy density ratio in figure 4.34. Apparently the multiple peaks have their origin in bow shock instabilities or nearby turbulence. However, they will not be discussed further except as they influence the energy density ratio, because they are clearly a microscopic rather than macroscopic feature of the sheath.

In the early part of the inbound sheath the spectra were especially broad. Perhaps these were associated with high energy particles in the bow shock wave. The energy ratio shows an average of about 40% of the energy density in the high energy part of the spectrum between day 84, 2200 UT and day 85, 0800 UT. Figure 4.36 shows the results of the curve fitting procedure discussed in section 3.2. During the region mentioned, high energy tails were measured with Kappa as great as 10. Later, in the more normal sheath an average Kappa of about 2.5 (illustrated by the horizontal line) is seen. Also a higher temperature was necessary to fit the broad
distribution functions. This figure shows that the energy ratio adequately displays the presence of the high energy tail and consequently it was the parameter chosen to be displayed in the majority of the data. Also, the curve fitting procedure was not often applicable on this large a percent of the data (86.2% of the data was fit with a chi square of less than 2 in this data segment).

LUNATION 6

The inbound sheath is seen in the Apollo 15 data in figures 4.37 and 4.38. The velocity, number density and pressure are seen to decrease across the sheath approaching the magnetopause. Again, intense low energy spectra are seen just inside the boundary (figure 4.37). The spectra are extremely sharp and show a very low percentage of energy in the tail. Apollo 14 data show similar characteristics except for a lower number density and pressure and a higher temperature due to the angular difference between the two detectors. The energy ratio is near 15% at the bow shock, but decreases to almost zero at the magnetopause. This suggests that the very narrow spectra are a characteristic of the sheath at this time rather than an angular effect.

The outbound sheath passage again contains the phenomenon of a sudden impulse followed by a storm. The magnetopause moves in past the moon's orbit around 400 UT, day 120 (figure 4.39) then recedes. After two more boundary crossings when the moon finally stays in the sheath, the energy ratio is low and the other parameters are normal. Figure 4.40 shows an increase in the energy ratio up to 50% during which the
LUNATION 6

Figure 4.37  The Apollo 15 distribution function spectra are shown for the dusk magnetosheath crossing.

Figure 4.38  Plasma parameters are plotted for the Apollo 15 dusk magnetosheath crossing.

Figure 4.39 - 4.40 Plasma parameters are plotted for the Apollo 14 dawn magnetosheath crossing.

Figure 4.41 Distribution function spectra are shown from the Apollo 14 dawn magnetosheath data.

Figure 4.42 Distribution function spectra are shown from Apollo 12 look periods in the dawn magnetosheath.
1972 APOLLO 15
DAY 115  HR 10  MIN 3

FIGURE 4.37
Figure 4.38

1972 APOLLO 15
DAY 115 HR 10 MIN 3
1972 APOLLO 14
DAY 119 HR 22 MIN 27

FIGURE 4.39
the other parameters remain relatively stable. Figure 4.41 shows the spectra during this event. If only an angular effect were involved the main peak might decrease thereby changing the ratio, but the tail itself would not increase as seen in the figure.

Apollo 12 data (figure 4.42) also record an increase in the energy ratio from 10% to 25% at the two points measured (see figure 4.6). A definite change is seen in the character of the spectra.

**LUNATION 7**

The inbound sheath is very similar to that of lunation 6. One difference is that the number density (Apollo 15 data) increases towards the magnetopause rather than the opposite as seen in lunation 6. The other parameters are relatively constant.

Of particular interest is the outbound sheath of this lunation. An unusually broad spectrum is seen in the Apollo 14 data (figure 4.43-4.44). The parameter plots (figure 4.45-4.46) show the highest energy ratio (70%) yet observed in sheath spectra. The bulk velocity is exceptionally high (~ 400 km/sec). This very high velocity begins decreasing after about 10 hours. The energy ratio also decreases at this time to around 50%. Pressure gradually decreases across the sheath. The Apollo 12 data (figure 4.47-4.48) (see figure 4.7 for location in sheath) show the same characteristics. Velocity decreases at the second look period, but is high again by day 153. The tail of the spectrum now contains multiple peaks at very high (> 2 keV) energies near the bow shock crossing (figure 4.47). They suggest a second particle distribution associated with
APOLLO 14 DISTRIBUTION FUNCTION SPECTRA FROM THE DAWN MAGNETOSHEATH CROSSING ARE SHOWN.

PLASMA PARAMETERS ARE PLOTTED FROM THE APOLLO 14 DAWN MAGNETOSHEATH DATA.

DISTRIBUTION FUNCTION SPECTRA FROM APOLLO 12 LOOK PERIODS IN THE DAWN MAGNETOSHEATH ARE GIVEN.

PLASMA PARAMETERS CALCULATED FROM THE APOLLO 12 DAWN MAGNETOSHEATH DATA ARE CALCULATED.
the bow shock wave. It is not clear how directional these particles are. Perhaps their diffusion is the source of the extremely high tail seen earlier by both detectors.

**LUNATION 8**

The inbound sheath is very stable for both Apollo 14 and 15. All the parameters are relatively constant through the sheath. There is only a slight increase of pressure and number density just before the magnetopause. The outbound sheath is likewise rather uneventful. It begins with the parameters constant at normal values. However, the last 30 hours before the bow shock crossing show a steady decrease in pressure, temperature, velocity and energy ratio. The spectra during this change are seen in figure 4.49. This appears to be exactly the opposite of the general trend observed as one approaches the bow shock.

**LUNATION 9**

Apollo 15 is looking only 2° away from the expected flow direction during the inbound sheath. The 15 data is very steady with a high pressure and number density as expected and a very low energy ratio. Apollo 14 shows a similarly steady sheath crossing. The parameters show a slight increase in the high energy ratio towards the magnetopause. The outbound sheath is again particularly stable. Perhaps its only noteworthy feature might be a low bulk velocity (~ 200 km/sec). Apollo 12 data confirms this particularly low velocity across the outbound sheath passage.

**LUNATION 10**

Apollo 15 data from the inbound sheath show high bulk velocity (~ 400 km/sec) which decreases in the last 30 hours
LUNATION 8

Figure 4.49 Some distribution function spectra in the dawn magnetosheath are plotted from Apollo 14 data.

LUNATION 10

Figure 4.50 The plasma parameters calculated from some of the Apollo 14 data in the dusk magnetosheath are shown.
before the magnetopause to a value of about 275 km/sec. Number density and pressure also decrease simultaneously. These decreases are also seen in Apollo 14 data (figure 4.50). The outbound sheath is again stable and of particularly low bulk velocity.

4.3 DISCUSSION OF OBSERVATIONS

A composite of 10 lunations of data reveals certain general tendencies of magnetosheath plasma. One of the more obvious examples is that the bulk velocity is always greater in the Apollo 15 data than in Apollo 14 data. Neugebauer (1972) used solar wind spectrometer (SWS) data from Apollo 14 and 15 to show that the velocity is always greater at the 15 site because the magnetic field is much weaker there (figure 2.9). Neugebauer shows that the expected change in velocity is

\[ \Delta v = \frac{B^2 - B'^2}{8\pi m_p n_v} \]

where \( B, n, \) and \( v \) are the values of the field, number density and velocity of the plasma before it is influenced by local lunar conditions. The observed velocity difference was somewhat less than the expected value. We would also expect the SIDE to see this velocity difference in the two sites. However, it cannot easily be separated from an angular effect. The peak of the particle distribution function decreases in velocity as the angle (\( \theta \)) with respect to the flow becomes greater (figure 4.51). The Apollo 15 detector in the inbound sheath is always 20° closer to the direction of flow than is the Apollo 14 detector. The difference in
Figure 4.51: The behavior of a model distribution function with the variation of the value of $\theta$ is illustrated here. A convected Maxwellian distribution function using the parameters as listed is plotted for 5 values of $\theta$. 
CONVECTED MAXWELLIAN

\[ E_b = 1000 \text{ ev} \]
\[ T = 10^6 \text{ K} \]
\[ n = 10 \text{ cm}^{-3} \]

\[ \theta = 0^\circ \]
\[ \theta = 20^\circ \]
\[ \theta = 36^\circ \]
\[ \theta = 45^\circ \]
\[ \theta = 56^\circ \]

FIGURE 4.51
look angle will effect the number density more than any other parameter. As θ increases by 20° the intensity of the spectrum decreases by about one order of magnitude. Since number density is used in calculating pressure, the pressure also varies with the angle θ as does number density.

All the data were processed with respect to the look direction of the detector. A value of θ = 0° was used in the distribution function equation. The resulting number density must be qualified. It is not an absolute number density of the phenomenon, but the value that would be inferred if the look direction of the detector were in the direction of the flow. The values of θ and N can be found independently by using simultaneous data from at least two instruments. Appendix A.6 gives this calculation. It was not used in this work because the normalization of the detectors has not been adequately done. Also, the effect of local surface fields was not known at the beginning of this work.

Figure 4.52 shows the angle of each detector with respect to the expected flow direction during the inbound and outbound magnetosheath crossings. As discussed in chapter 2 the relative angle is a constant for each lunation, although both detector look direction and flow direction change across the sheath. Perturbations in the lunar orbit are seen to vary this angle by as much as 10°. The data do not reflect this variation, probably because of the magnitude of other effects such as its response to the changing interplanetary conditions.
The calculation of the angle of the detector with respect to the expected flow direction is illustrated in Figure 2.11 for a single lunation. This angle is almost constant for a single magnetosheath crossing. Thus a single value of $\theta$ is obtained for each instrument for each sheath crossing. These values of $\theta$ are plotted in this figure for the ten lunations studied in this paper.
ANGLE WITH RESPECT TO THE FLOW FOR 10 LUNATIONS

INBOUND

OUTBOUND

\( \theta \)

1 2 3 4 5 6 7 8 9 10 1 2 3 4 5 6 7 8 9 10

LUNATION

LUNATION

FIGURE 4.52
CHAPTER 5

SUMMARY AND INTERPRETATION OF THE OBSERVATIONS

5.1 MAGNETOSHEATH STRUCTURE AT 60 RE

The dayside data of the SIDE from 10 lunar orbits were presented in Chapter 4. There are 10 passages through the earth's magnetotail requiring 2 to 3 days for each magnetosheath crossing. Observations include both temporal and spatial variations. A summary of the bulk flow parameters calculated for the magnetosheath plasma is given in Figures 5.1 to 5.4. In most cases only the boundary values were plotted and joined by a straight line. No attempt was made to show the detailed variations. Temperature (Figure 5.1) is apparently the most consistent parameter. It shows a general trend to decrease toward the magnetopause and increase at the bow shock. The calculations of Spreiter and Alksne (1969) predict this behavior. Figure 5.5 contains sketches of expected parameters. From this figure it is suggested that the trend in the temperature difference would be accentuated at further distances down the flanks of the sheath. We observe up to a factor of 2 between magnetopause and bow shock values. The orbits that do not show an increase at the bow shock appear relatively constant across the sheath.

Velocity data, shown in Figure 5.2, are not as consistent. No general behavior pattern is apparent. From the plot of
Figure 5.1  Temperature is plotted for the 10 lunations. Average values at the boundary crossings were used in this plot. Detailed information is omitted in order to look at the general structure of sheath crossings. The three instruments are indicated by dashed lines (Apollo 14), solid lines (Apollo 15) and dots (Apollo 12). The range of the Y axis is 5 to $15 \times 10^5$°K.

Figure 5.2  Velocity is plotted for the 10 lunations. The Y axis is 100 to 500 km/sec. Boundaries are labeled BS (bow shock) and MP (magnetopause).

Figure 5.3  Pressure is plotted for the 10 lunations in the range $10^{-11}$ to $10^{-9}$ dynes/cm$^2$.

Figure 5.4  The energy density ratio is plotted in the range 0 to 100% for all 3 instruments for the 10 lunations.
FIGURE 5.1

TEMPERATURE ($\times 10^5^\circ K$)

LUNATIONS

1. Ap14
2. Ap12
3. Ap14
4. Ap15

MPS

DUSK

MP

DAWN

BS
FIGURE 5.2
ENERGY DENSITY RATIO (percent)

FIGURE 5.4
calculated lines of constant velocity (Figure 5.5), velocity is expected to increase from the bow shock in to the magnetopause. The magnitude of this variation is less than that for temperature. The temporal variations are much larger than the laminar flow variations, as exhibited by the fluctuations in Figure 5.2. The most significant observation in this figure is that the Apollo 15 velocity is always greater than the Apollo 14 velocity. This was discussed in Chapter 4 and is attributed to the higher magnetic field at Apollo 14 and the detector look angle with respect to the angle of flow. In the dawn side of the 10th lunation, Apollo 15 still shows a higher velocity when it has the greatest look angle with respect to the flow. This indicates that the effect of the local magnetic field as observed by Neugebauer (1972) is also the most significant effect in S1DE data.

Pressure (Figure 5.3) is the most sensitive parameter to the look angle. Thus it appears as much as an order of magnitude different between Apollo 15, looking almost into the flow, and Apollo 14, looking 20° away. Pressure is the product of number density and temperature. From the number density plot of Figure 5.5, we would expect a decrease from the bow shock to the magnetopause. This decrease is observed on most of the dusk lunations in Figure 5.3. Again, temporal variations mask the spatial structure.

The energy density ratio (Figure 5.4) is expected to decrease from the bow shock to the magnetopause for a reason which is independent of the other parameters. This ratio is a measure of the turbulence in the sheath putting energy into
Figure 5.5

Calculated variation of density, velocity, temperature, and mass flux through the magnetosheath for various values of $M_A$ and $\gamma$, after Spreiter et al., 1969.
Density and temperature fields for supersonic flow past the magnetosphere
$M_{\infty} = 8.71, \gamma = 2$

(a)

Velocity and mass flux fields for supersonic flow past the magnetosphere
$M_{\infty} = 8.71, \gamma = 2$

(b)

FIGURE 5.5
a high energy tail. If waves are produced or amplified at the bow shock then the turbulence should be greater at the shock as observed by Kaufman (1970). The dusk sheath reflects this trend for 7 of the 10 orbits. The remaining ones are constant rather than decreasing. Only 3 orbits in the dawn sheath show this trend. The energy density ratio appears more unstable in this side. In looking at this asymmetry it is important to notice that the ratios are not particularly higher on the dawn side. Rather than more turbulence in the distribution function, the dawn sheath is more random. Pressure also was more random in the dawn sheath.

In summary, the parameters of temperature and pressure behave as predicted by the Spreiter-Alksne calculations if they can be extrapolated to 60 \( R_e \). Velocity is observed to be decreased by large local surface magnetic fields at the 12 and 14 ALSEP sites. Temporal variations are probably very significant in this data. The energy density ratio indicates greater turbulence at the bow shock than at the magnetopause for the dusk sheath. It shows the dawn sheath parameters to be less stable than the dusk sheath parameters.

5.2 CORRELATION WITH GEOMAGNETIC ACTIVITY

The solar wind data and geomagnetic data that are available from the U.S. Department of Commerce SOLAR-GEOPHYSICAL DATA prompt and comprehensive reports were studied for these 10 months. Three instances of specific correlation were observed. The first was an increased velocity and number density in the solar wind on day 27. This agrees with the
higher velocity observed by both detectors as they re-entered the sheath on that day. The higher velocity region was shown in the discussion of lunation 2. The other two events were sudden impulses that were observed on earth and followed by magnetic storms. In lunations 5 and 6 (Figures 4.5 and 4.6) the magnetosheath was observed to be compressed after these magnetically active times.

Besides specific events, there is a gross relationship of sheath spectra to geomagnetic activity. Figure 5.6 presents the value of Kp taken for 3-hour averages and plotted along the moon's orbit in SM coordinates. The boundary crossings seen earlier in Figure 4.11 are superimposed on this plot to show the sheath position as it relates to geomagnetic activity. Note the compressed magnetopause in lunations 2, 5 and 6 because of special events mentioned above. Also, the magnetopause crossing for 9 of the 10 dawn crossings were inside the empirical boundary indicating the abration of the solar wind direction. This would move the empirical boundaries to the left by .1 radian. Most of the large geomagnetic activity (lunations 5, 6, 9) occurred while the moon was in the tail rather than in the sheath (lunation 4).

In order to study the relationship of sheath parameters to Kp, the sheath crossing region was divided into 4 parts. The mean value of Kp was taken for each of these segments. Then the 4 values were averaged to give a single value per sheath crossing. These average values were accumulated for the 10 lunations. The five calculated parameters were averaged in exactly the same manner, dividing the sheath
The summary of magnetosheath observations from 10 lunations (Figure 4.11) is plotted over a graph of average values of $K_p$ as a measure of geomagnetic activity.
crossing into 4 regions and averaging the mean values from the 4 regions. Plots of Kp and the parameters for the 10 inbound and outbound sheath crossings for each instrument are given in Figure 5.7.

For the inbound sheath the curve of the energy density ratio seems to follow that of Kp quite well. Velocity and temperature appear to be somewhat correlated but to a lesser degree. Pressure, which is directly related to the total energy density is not correlated with Kp at all. Number density is also apparently unrelated and furthermore, it is not closely related to the angle \( \theta \) in Figure 4.52 over the 10 lunations as one might expect. However, the magnitude of the values from the three instruments with respect to each other is in agreement with their relative angles. That is, Apollo 15 always reports a higher number density in the inbound sheath than Apollo 14 since it is closer to the flow direction.

It is important to note that the detector farther from the flow direction (Apollo 14) reports a greater energy density ratio. This is probably an indication that the dispersion of particles in velocity space is isotropic. That is, the diffusion in a single direction is not in proportion to the bulk flow in that direction. Looking at the spectral plots the intensity of the tail was comparable for all 3 instruments regardless of the intensity in the bulk flow. The high energy tail seems to be a more isotropic component of the spectrum. Howe (1971) had reported the double peaked ions at the bow shock to be in a different
A summary of plasma parameters is given for data from both the dusk and dawn sheath crossings for 10 lunations. Data points from the 3 instruments are identified by an X (Apollo 14), solid dot (Apollo 15) and open dot (Apollo 12). One average value of a parameter is taken for each sheath crossing for a single instrument. Above the parameter plots, a plot of average $K_p$ is given. For each sheath crossing, $K_p$ was averaged during the time the moon was in the magnetosheath.
direction from the bulk flow. The sudden appearance and disappearance of multiple peaks in individual spectra is a directional effect. The macroscopic view of the data indicates a degree of isotropy.

For the outbound sheath (Figure 5.7) the parameters seem totally unrelated to Kp. Velocity and energy density ratio are somewhat related to each other. But energy density ratio is not related to Kp. Note that their peaks are one lunation apart possibly causing their curves to appear similar, but showing no relation between them.

A linear regression analysis was run on each of these curves with respect to Kp. The correlation coefficient r for each of the variables is given in Table 5.1. A coefficient r=1 indicates perfect correspondence and r=0 indicates random data. Consequently it is important to note the strong correlation of velocity and energy density ratio on the inbound side and almost no correlation on the outbound side.

To further emphasize this correlation the energy density ratio (Apollo 14 data) is plotted versus a composite of Kp (Figure 5.8). Here Kp has been summed over a normalized region. (Dividing by the region size converts these numbers to an average Kp as used in Figure 5.7.) A least squares fit was attempted on both the dusk and the dawn data. The fit is plotted for the dusk data, but is meaningless for the dawn data since the correlation coefficient indicates random data.
TABLE 5.1
LINEAR REGRESSION OF $K_p$ VERSUS PARAMETERS

Gives values of the correlation coefficient $0 < r < 1$
where $r = \pm 1$ is a perfect correlation
$r = 0$ is random data

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>INBOUND APOLLO 14</th>
<th>INBOUND APOLLO 15</th>
<th>OUTBOUND APOLLO 14</th>
<th>OUTBOUND APOLLO 12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy density ratio</td>
<td>.88</td>
<td>.67</td>
<td>.05</td>
<td>.30</td>
</tr>
<tr>
<td>Velocity</td>
<td>.79</td>
<td>.77</td>
<td>.20</td>
<td>.13</td>
</tr>
<tr>
<td>Temperature</td>
<td>.76</td>
<td>.36</td>
<td>.36</td>
<td>-.41</td>
</tr>
<tr>
<td>Number density</td>
<td>-.36</td>
<td>.20</td>
<td>-.27</td>
<td>-.32</td>
</tr>
<tr>
<td>Pressure</td>
<td>.19</td>
<td>-.17</td>
<td>-.06</td>
<td>-.11</td>
</tr>
</tbody>
</table>
The average energy density ratio for each of the 10 lunations was plotted versus the value of $K_p$. The composite $K_p$ is a calculated value that is proportional to the average $K_p$. A linear regression gives a straight line fit to the dusk data. The dawn data were random as seen by a correlation coefficient ($r$) of .05.
**DUSK**

\[ r = 0.88 \]

\[ Y = 0.64 \quad X = -6.67 \]

**DAWN**

\[ r = 0.05 \]

**FIGURE 5.8**
Thus, turbulence in the dawn sheath is not at all correlated with geomagnetic activity, while the dusk sheath turbulence shows a strong correlation.

To understand this result we must look at two things: 1) what correlation with geomagnetic activity means and 2) what is indicated by the asymmetry. First, it is well known that geomagnetic activity is correlated with interplanetary conditions. Both an increase in solar wind speed (Ballif et al., 1969) and an increase in the magnitude of the interplanetary magnetic field (Shatten and Wilcox, 1967) are correlated with an increase in Kp. An increase in the momentum flux of the solar wind is known to compress the geomagnetic cavity and boundary locations are related to Dst (Freeman, 1964). Thus solar wind energy must be transmitted through the magnetosheath to reach the magnetosphere. However, specific correlation of sheath activity with geomagnetic activity has not been made previously. Turbulence in the particle data, indicated by a high energy tail (\(x=2\), Cauchy distribution function), has been used to characterize enhanced sheath activity (Formisano et al., 1973). Here the energy density ratio has been used to indicate a high energy tail. Correlation of the tail with Kp shows that diffusion of particles in velocity space (turbulence) is a part of the mechanism by which energy is transmitted from the interplanetary medium.

This correlation of the tail with Kp is strong on one side of the sheath. The amount of turbulence was not seen to be greater on one side than the other. There are many reasons
that an asymmetry in the opposite sides of the sheath is not at all surprising. First, the field configuration drawn by Greenstadt (Figure 1.4) shows both types of shocks (perpendicular and oblique) occurring simultaneously on opposite sides of the magnetosphere. They are entirely different phenomena. The post-shock field is much more disturbed in the oblique shock and disturbances in the plasma are expected. Greenstadt observed the oblique shock to occur 50% more often in the dawn magnetosheath. Fairfield (1971) had already observed the dawn magnetosheath field to be more disturbed than the dusk field. Howe (1971) observed the motion of the bow shock to be greater on the dawn side. He saw twice as many shock crossings on the dawn side as on the dusk side. From SIDE results, this asymmetry in the opposite sides of the magnetosheath is reflected in the particle data as well as the field data and boundary motion.Apparently the dawn sheath is subject to disturbances of its own due to the nature of the interaction on that side. The dusk side exhibits more clearly the transmission of energy to the magnetosphere. The dawn side is not significantly more turbulent, but is not responsive to Kp.

The question arises as to what mechanism might be present in the dawn and not the dusk sheath that would be independent of Kp. This observed asymmetry may give added insight in considering the dynamic processes involved in the sheath. Three methods of acceleration have been suggested to contribute to the high energy particles. Stochastic acceleration is
generally applied to the very high energy particles (10-30 kev electrons). Therefore it does not apply to the present problem of explaining the high energy tail. Wave particles interactions, of which Landau damping is the prime example, most probably are responsible for transferring energy into the tail of the particle distribution. Such interactions would be present on both sides of the sheath. However, Fermi acceleration has not been seriously considered. For the field configuration of Figure 1.4 it would apply only to the dawn side since it involves a mirroring process between the incoming magnetic field and boundary field of the magnetosphere (Hess, 1968). Such an asymmetric process might mask any correlation with Kp on the dawn side, and explain the asymmetry in the observations. It might be a desireable objective for further investigation to determine whether this mechanism is significant enough to contribute to the observed high energy tail.

5.3 MAGNETOSHEATH IONS IN THE TAIL

Bursts of very low energy ions (≤100eV) in the geomagnetic tail were first pointed out in the summary figures of integral flux (figures 4.3, 4.5, 4.6, and 4.9). These were notable since they were almost as intense as magnetosheath fluxes and they appeared to be isolated bursts in the tail. Later, in the average spectra plots, low energy ions were noticed at both dusk (figure 4.13) and dawn (figure 4.27) magnetopause crossings. Their association with magnetosheath ions was suggested in these figures because of their proximity to the sheath and the similarity of their spectrum with that of
magnetosheath ions. Looking at the individual spectra at a magnetopause crossing generally reveals a gradual transition from the low energy (<100eV) spectra to the normal magnetosheath spectra (peaked at ~500eV).

These observations near the magnetopause led to the identification of the low energy particles as the magnetotail boundary seen by Hones et al. (1972a), Intriligator et al. (1972a), and Howe et al. (1972b) and most recently discussed by Akasofu et al. (1973). They observe a layer of low energy ions that outline the shape of the plasma sheet. Figure 5.9 is a plot of Akasofu's observations of the boundary layer with respect to the neutral sheet. In the center of the tail they are closer to the mid-plane than at the flanks. The SIDE observations become much more reasonable in light of this picture. The boundary layer is observed when the moon crosses from the magnetosheath into the plasma sheet. If it crosses into the tail lobes, then the low energy ions are not observed at the magnetopause crossing. However, far away from the sheath, low energy ions will be observed as the moon enters the plasma sheet from the high latitude lobes of the tail. The locations of SIDE observations are plotted in solar magnetospheric coordinates in figure 5.10. This plot is not centered on the calculated position of the neutral sheet as is Akasofu's plot (figure 5.9). However, this plot shows SIDE data to be in quite reasonable agreement with the magnetotail boundary layer concept.

Three lines in figure 5.10 show extended observations of the boundary layer in lunations 4, 5, and 9. Lunations 5 and 9 both show periods of intense magnetic activity in the tail crossing (figure 5.6). At 1 km/sec, the moon may be following
Figure 5.9

A map shows the segments of Vela orbits through the magnetotail, along which the detectors sensed proton fluxes characteristic of the plasma sheet (heavy lines) and the boundary layer (thin lines). The coordinates are solar magneto- spheric longitude $\phi_{SM}$ and distance from the neutral sheet $dZ_{SM}$.

(Akasofu et al., 1973)

Figure 5.10

A map shows SIDE data in the magnetotail. Single events of boundary layer fluxes are labeled as well as extended periods of boundary layer observations. Magnetopause crossings at which no boundary layer was observed are labeled (X) in the figure. The coordinate system is the solar magneto- spheric longitude (SMLOA) and latitude (SMLA) of ALSEP.
OBSERVATIONS OF BOUNDARY LAYER IN THE TAIL

Figure 5.10

- Extended period of boundary observations
- Boundary layer fluxes
- MP crossing but no boundary layer
- Vague boundary crossing

SMLOA

(SMLA)
the boundary motion or remaining in the boundary for some time. The long vertical motion (≤6 Re) in lunation 9 boundary layer observations may indicate a thicker boundary during strong geomagnetic activity. A thickness of ~1000 km has been observed for the boundary layer near the mid-plane. It was observed to be much thicker near the flanks of the tail (Hones et al., 1972). In general, the location of the observations depends on the configuration of the tail at the time of observation. This configuration is a direct function of geomagnetic activity.

The intensity and energy of the boundary ions vary considerably between observations. A sample scan of the digital data was made in order to correlate these events with Kp. Absolutely no correlation was observed for either intensity or energy. This result is not conclusive, however, it suggests that perhaps other relationships are more important, such as position with respect to the neutral sheet.

The energy spectra of the boundary layer ions peaks between 50 and 100 ev. It is very narrow, and no higher energy ions are present. Figure 4.23 shows how flat the high energy range of the spectrum is for even a very intense boundary layer. Compare this with the magnetosheath spectra in figure 4.29.

Akasofu always observed a lower number density as well as a lower velocity in the boundary layer. Temperature was lower than or comparable to magnetosheath temperature. SIDE data are consistent with these observations, although the number density of the boundary was observed to be almost comparable to that of the magnetosheath.

The source of these ions is thought by Hones (1972b) to be the magnetosheath ions at the polar cusps. He uses Frank's
model of field lines, which maps the polar field lines back into the tail. These lines do not enter the plasma sheet, but surround it. Hones suggests that the boundary layer ions are magnetosheath ions that have direct access at the polar cusps and follow the polar field lines back into the tail.

Hill (1973) has suggested that the boundary layer ions could be explained by Alfven's neutral sheet model concept of direct access at the front of the magnetosphere. This access is not limited to the cusp region, and would cause ions to flow directly down the boundary for the case of parallel fields at the boundary.

Neither model has been thoroughly examined in view of detailed observations. The main problem that remains to be solved is that of explaining the observed energy spectrum. A mechanism that will decrease the flow energy and leave the temperature constant or even decrease the temperature has not yet been explained. However, the importance of these observations is that they do exhibit the direct access of magnetosheath ions to the tail. It is important that this layer is observed as a permanent feature of the tail and only its location is related to Kp.
CHAPTER VI

CONCLUSIONS

Plasma observations of the earth's magnetic tail and transition regions were made from the lunar orbit (60 Rₑ) for 10 lunations. A composite of the plasma parameters calculated from the observed distribution function were used to describe the structure of the sheath at this distance. This research has been aimed at understanding the role of the magnetosheath in the earth's interaction with the solar wind. Energy is transferred from the solar wind to the earth's magnetosphere and the magnetosheath is a transition region between the two. Two methods of energy transfer were considered 1) Magneto-hydrodynamic coupling and 2) Direct particle access.

First, the structure of the magnetosheath was described in terms of its plasma parameters. Pressure and temperature tend to decrease across the sheath from the bow shock to the magnetopause. This behavior was predicted by the laminar flow theory of Spreiter and Alksne (1969). Velocity does not show a definite spatial structure across the sheath. A comparison of the data from 3 ALSEP sites on the moon showed that the velocity observed is strongly influenced by the local surface magnetic field. A weak field at the Apollo 15 site accounts for a higher velocity consistently observed by Apollo 15. Velocity is also strongly influenced by temporal variations in the solar wind. In general, the structure of the dawn sheath parameters was not as well-defined as that of the dusk sheath parameters.
The most immediate evidence of the earth-sun interaction is seen in the fluctuations of the magnetosheath boundaries. The most extreme boundary motions are correlated with the occurrence of a sudden impulse in geomagnetic data followed by a magnetic storm. The average boundary locations during the 10 lunations agree with earlier boundary observations. Also, the expected aberration of the solar wind direction is evident in this data.

Magnetohydrodynamic coupling involves plasma processes whereby energy is transferred between fields and particles. The participation of particles in the energy transfer is indicated by their distribution function in velocity space. 'Turbulence' has been used to mean the presence of such transfer processes causing a diffusion of particles in velocity space, or a high energy tail on the particle distribution function.

Turbulence was observed to decrease from the bow shock to the magnetopause in the dusk sheath. This observation agrees with Kaufman's (1970) conclusion that the dominant magnetoacoustic waves are produced or amplified in the bow shock. This assumes that wave-particle interactions are used to produce the turbulence. The dawn sheath does not show a definite structure in the turbulence observed.

Correlation of turbulence in the sheath with geomagnetic activity shows a very strong correlation in the dusk sheath, and no correlation in the dawn sheath. This striking asymmetry emphasizes that the dawn and dusk sheaths are two very different phenomena. The sheath field configuration resulting from a 45° interplanetary field is parallel to the boundary on the
dusk side and almost perpendicular on the dawn side. Such an oblique field configuration is most commonly observed. Consequently, different physical processes are expected in different sides of the sheath. Fermi acceleration, applicable only on the dawn side in such a configuration, is suggested as a possible source of turbulence in the dawn sheath as well as the wave-particle interactions to mask a dependence on $Kp$. The most important result, however, is that SIDE particle data confirm an asymmetry in plasma that has previously been reported only in field data and in boundary motions.

Finally, the direct access of magnetosheath ions into the magnetosphere is also observed. SIDE data is able to identify the boundary layer of the magnetotail discussed by Akasofu (1973). These low energy ($\leq 100 \text{eV}$) ions were observed at magnetopause crossings and at entrances to the plasma sheet which were further out in the tail. They were observed to be more isotropic than ions in the magnetosheath, but having a similar distribution function at a lower bulk velocity and number density. A very important SIDE observation is the increase in the energy of these ions as they approach the sheath boundary. This may suggest some viscosity in the boundary region, first proposed in the Axford and Hines model. But the source of these particles is presently thought to be direct entry of sheath particles at polar cusps or the front region of the magnetosphere, flowing back along polar field lines.

In summary, this paper has presented evidence for the participation of the magnetosheath in the earth-sun interaction both indirectly by turbulence in the plasma and by direct access
of sheath particles into the tail boundary. The plasma shows an asymmetric relationship to geomagnetic activity on opposite sides of the sheath. The general structure of plasma parameters is that predicted by laminar flow.
APPENDIX A.1

NPAAK FORMAT

200 BPI magnetic tapes, 1 record consists of 18, 24-bit words written in binary on 7 track tape, 6 records = 1 block.

<table>
<thead>
<tr>
<th>WORD</th>
<th>CONTENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>DAY</td>
</tr>
<tr>
<td>2</td>
<td>HOUR</td>
</tr>
<tr>
<td>3</td>
<td>MINUTE</td>
</tr>
<tr>
<td>4</td>
<td>MILLISECONDS</td>
</tr>
<tr>
<td>5</td>
<td>Z = NUMBER OF PREVIOUS FRAMES OMITTED BECAUSE OF ZERO DATA</td>
</tr>
<tr>
<td>6</td>
<td>SIDE FRAME NUMBER</td>
</tr>
<tr>
<td>7</td>
<td>ANALOG SUBCOMMUTATOR</td>
</tr>
<tr>
<td>8</td>
<td>TID STEPPING VOLTAGE ON CURVED PLATES</td>
</tr>
<tr>
<td>9</td>
<td>TID COUNTING RATE</td>
</tr>
<tr>
<td>10</td>
<td>STATUS SUBCOMMUTATOR</td>
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<tr>
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<td>VELOCITY FILTER VOLTAGE</td>
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</tr>
<tr>
<td>13</td>
<td>MA COUNTING RATE</td>
</tr>
<tr>
<td>14</td>
<td>TID QUALITY WORD+</td>
</tr>
<tr>
<td>15</td>
<td>MA QUALITY WORD</td>
</tr>
<tr>
<td>16</td>
<td>MODE &amp; STATUS WORD</td>
</tr>
<tr>
<td>17</td>
<td>blank</td>
</tr>
<tr>
<td>18</td>
<td>blank</td>
</tr>
</tbody>
</table>
*CODE FOR MODE OF INSTRUMENT

0  NORMAL
1  RESET SIDE FRAME AT 10 AND TIMES 10
2  RESET SIDE FRAME AT 10
3  RESET SIDE FRAME AT 39
4  RESET VELOCITY FILTER AT 9 (SF GOES 0-127)
5  RESET SIDE FRAME AT 79
6  RESET SIDE FRAME AT 79 AND RESET VF AT 9
7  TIMES 10 ACCUMULATION MODE
8  PRESUMED TO BE TIMES 10 MODE
9  CONTINUOUS CALIBRATION
10  VF SEEMS TO BE IN RESET AT 9
11  RESET SIDE FRAME AT 39 AND TIMES 10
12  RESET VELOCITY AT 9 AND TIMES 10
13  RESET SIDE FRAME AT 79 AND TIMES 10
14  RESET SIDE FRAME AT 79 AND VF AT 9 AND TIMES 10
15  CONTINUOUS CALIBRATION AND TIMES 10
16  MISSING FRAME OR FRAMES
Number the bits of a binary word such that the number of the bit corresponds to the power of 2 represented by that bit.

<table>
<thead>
<tr>
<th>WORD</th>
<th>BIT NO.</th>
<th>CONTENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>TID QUALITY WORD</td>
<td>0-3</td>
<td>TRACKING STATION NUMBER</td>
</tr>
<tr>
<td></td>
<td>4-9</td>
<td>BIT ERROR RATE OF EVEN BENDIX FRAME</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>PARITY FLAG OF EVEN BENDIX FRAME</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>TID FLAG = 1 IF CHANNELTRAN HIGH VOLTAGE, OR TID STEPPING VOLTAGE OUT OF TOLERANCE</td>
</tr>
<tr>
<td></td>
<td>12-24</td>
<td>ZERO</td>
</tr>
<tr>
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<td>BIT ERROR RATE OF EVEN BENDIX FRAME</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>PARITY FLAG OF EVEN BENDIX FRAME</td>
</tr>
<tr>
<td></td>
<td>7-12</td>
<td>BIT ERROR RATE OF ODD BENDIX FRAME</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>PARITY FLAG OF ODD BENDIX FRAME</td>
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<tr>
<td></td>
<td>14</td>
<td>MA FLAG = 1 IF CHANNELTRAN HIGH VOLTAGE OR MA STEPPING VOLTAGE OR VELOCITY FILTER VOLTAGE OUT OF TOLERANCE</td>
</tr>
<tr>
<td></td>
<td>15-24</td>
<td>ZERO</td>
</tr>
<tr>
<td>MODE-STATUS WORD</td>
<td>0</td>
<td>GROUND PLANE VOLTAGE FLAG OF PREVIOUS FRAME</td>
</tr>
<tr>
<td></td>
<td>1-5</td>
<td>MODE OF PREVIOUS FRAME</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>MA FLAG OF PREVIOUS FRAME</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>TID FLAG OF PREVIOUS FRAME</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>HIGH VOLTAGE FLAG OF PREVIOUS FRAME</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>HIGH VOLTAGE FLAG = 1 IF CHANNELTRAN HV OUT OF TOLERANCE</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>GROUND PLANE VOLTAGE FLAG</td>
</tr>
<tr>
<td></td>
<td>11-15</td>
<td>MODE*</td>
</tr>
<tr>
<td></td>
<td>16-24</td>
<td>ZERO</td>
</tr>
</tbody>
</table>
APPENDIX A.2

C EDIT ALSEP/SIDE DATA
C EDIT THIS PROGRAM CONVERTS THE COUNTING RATES GIVEN ON NPAK TAPES
C TO DIFFERENTIAL FLUX AND CALCULATES THE INTEGRAL FLUX
C FROM EACH ENERGY SPECTRUM
C PRINTOUT FORMAT: MR/SEC*(DIFF FLUX IN EACH OF 20 ENERGY CH)100,
C (INTEGRAL FLUX FROM DIFF SPECTRUM)10000

DIMENSION JARAY(16), INT(6), IFLAG(127), KECT(127),
6ITIME(127), KCTI(127), INTG(6), E(20)
INTEGER*4 STD, STM, STH, STS, AZS, ALSEP, YEAN, SERIAL
REAL KECT, INTG
DATA E/350, 325, 300, 275, 250, 225, 200, 175, 150, 125, 100,
675, 50, 25, 10, 7, 5, 3, 2, 1,
CALL ERRSET (215, 100, 100, 1, 0)
310 FORMAT (41S, 6X, 30HTOLERANCE HESY OR HV OR PARITY, 5X, 9HRAMF = .15)
320 FORMAT (41S, 6X, 12UNUSUAL MODE)
330 FORMAT (41S, 2X, 2HTO, 15, 1ANDDISCONTINUOUS DATA)
360 FORMAT (2X, 3HDAY, 14, 5X, 2HHR, 14, 5X, 3MIN, 14, 5X, 3SEC, 14)
IC=0
NBG3=0
NBG4=0
READ (5, 3) STD, STM, STH, STS, IN
C IN: INSTRUMENT NUMBER
3 FORMAT (5I3)
JDAY=STD
JHR=STM
JMIN=STM
JSEC=STS
KMB=STM
12 JSTORE=1
IMODE=0
IVOLT=0
DO 10 I=1, 6
101 INTG(M) = 0
DO 97 I=1, 127
KECY(I) = 0
IFLAG(I) = 1
97 ITIME(I) = 0
IFL=1
NDEL = 0
13 READ (11, 20, ERR=880, END=999) JARAY
20 FORMAT (18A3)
I=(JARAY(6)-64)/256
JMIN=(JARAY(3)-64)/256
JSEC=(JARAY(4)-64)/256000
15 JDAY=(JARAY(1)-64)/256
JHR=(JARAY(2)-64)/256
JMIN=JMIN
MSEC=JSEC
PRINT 360, JDAY, JHR, JMIN, JSEC
IF (STM.EQ.JHR) GO TO 13
IFL=LH.
GO TO 13
C ITIME IS MEASURED TO THE HOUR
14 ITIME(I)=JSEC* 60*JMIN
JARAY(14)=(JARAY(14)-64)/256
JARAY(16)=(JARAY(16)-64)/256
JARAY(11)=(JARAY(11)-64)/256
JARAY(2) = (JARAY(2)-64)/256

C TEST FOR TOLERANCES AND PABITY
31 IF ((JARAY(14)/1024).LT.1) GO TO 35
32 IFLAG (1)=2
31 IF (((JARAY(16)-(JARAY(16)/1024)*1024)/512).LE.0) GO TO 34
C HV IS OFF
C
300 FORMAT (20H HV IS OFF AT FRAME, i4//)
31 READ (11,20,ERR=886,END=999) JARAY
JARAY(16) = (JARAY(16)-64)/256
31 IF (((JARAY(16)-(JARAY(16)/1024)*1024)/512).GT.0) GO TO 31
JDAY=JARAY(1)-64)/256
JHR=(JARAY(2)-64)/256
IFLAG(JSTORE)=7
BACKSPACE 1
GO TO 85
34 IVOLT=IVOLT+1
IF (IVOLT.GT.5) GC TO 35
PRINT 310,JARAY(1),JARAY(2),JMIN,JSEC,1

C TEST MODE AND GAP
35 IF ((JARAY(16)/2048).LT.1) GO TO 60
36 IF ((JARAY(16)/32768).GE.1) GO TO 40
C UNUSUAL MODE
38 IFLAG(1)=4
IMODE=1+IMODE
138 PRINT 320,JARAY(1),JARAY(2),JMIN,1
139 GC TO 60
C DISCONTINUOUS DATA (MAY ALSO BE IN UNUSUAL MODE)
40 PRINT 330,JDAY,KHR,KMIN,JSTORE,1
IDELTA+1-JSTORE
IFLAG(1)=3
NDEL = JSEC -KSEC+60*(JMIN -KMIN))+768*(JARAY(2)-KHR))
41 IF (NDEL.GT.1) 42,50,50
42 IF (IDELTA 1) 50,50,45
50 IFLAG(1)=5
IF (KHR+NE,JARAY(2)) IFLAG(1)=6
52 PRINT 332,JSTORE
332 FORMAT (110,10HBLCK SKIP)
GO TO 85
49 GO 47 K=JSTORE,1
47 IFLAG(1)=3
60 IF (KHR+EQ,JARAY(2)) GO TO 62
61 IFLAG(1)=6
62 JSTORE=1
KDAY=JARAY(1)
KMIN=JMIN
KSEC=JSEC
KECT(1)=JARAY(2)-64)/256
C SUBTRACT BACKGROUND
65 IF ((1-121)/13,7C,75
70 NBG1=KECT(121)
75 IF (1-NC.125) GO TO 13
80 NBG2=KECT(125)
85 NBG=(NBG1+NBG2+NBG3+NBG4)/4
NBG1=NBG1
NBG4=NBG2
C CONVERT TO DIFFERENTIAL ENERGY SPECTRUM
C
C ASSUME IOPC PASS BAND FOR ALL ENERGY CHANNELS
C
85 DD 95 L=1:6
W=M-1
M=11TIME(M*20+1))/60
MS=11TIME(M*20+1))-W*60
C
C 93 DD 93 K=1:20
C KECT(J)=(KCT(J)-NEG)/E(K)*10000
KCT(J)=KCT(J)/100
IF (KCT(J)>2.93,93
C 92 KCT(J)=0
C
C CONTINUE
C
DC 94 K=1:19
J=K*M+20
C INTEGRAL FLUX = INTEGR(15000)
94 INTEGR(M+1)=(KCT(J+1)+KCT(J))/2*10*(E(K)-E(K+1)) + INTEGR(M+1)
C INTEGRAL FLUX = INTEGR(15000)
C
95 PRINT 400, MM, MS, (KCT(K*M+20), K=1:20), INTEGR(L)
C 400 FORMAT (1X,212,2016,1R)
C IF IFL=LE IFLAG(1)) GO TO 96
C 501 IFLAG(1) = IFL
C 96 WRITE (6) JDAY, JHR, MIN, SEC, (KCT(I), I=1,120), (IFLAG(I), I=1,120)
C 66TIME(I), I=1,120), INTEGR, NBG
C
C 500 IF (IFLAG(1)>0) GO TO 110
C
C LHMA
C 110 GO TO 12
C
C LABEL ROUTINE
C 800 CALL LABEL (AZS,ALSEP,YEAR, SERIAL, INDIC)
C 810 PRINT 820
C 820 DD 810 I=1:20
C
C SEARCH ROUTINE
C 820 READ (1,20+END=900) JARAY
C 802 JDAY=JARAY(1)+64)/256
C 802 IF (ST=JDAY) 13, 802, 801
C 802 JHR=JARAY(2)+64)/256
C 803 JMIN=JARAY(3)+64)/256
C 803 IF (ST=JHR) 803, 803, 801
C 900 PRINT 901
C 901 FORMAT (1HEND. SEARCH*)
C 901 FORMAT (1HEND CF FILE)
C 820 FORMAT (6M LABEL)
C 830 FORMAT (7H TWENTY)
C
C 999 STOP
C
END
APPENDIX A.3

C PSK ALSEP/SIDE DATA MARTHA FENNER
C PSK THIS PROGRAM CALCULATES THE POWER SPECTRAL DENSITY FUNCTION
C OF THE INTEGRAL FLUX BY TAKING THE FOURIER TRANSFORM
C OF THE AUTOCORRELATION FUNCTION
C NOTE INTEG VALUES CANNOT BE ZERO (INTEGRAL<100CC)
C NR = NUMBER OF RECORDS USED
C N = NUMBER OF SPECTRA USED = 6*NR
       DIMENSION IBUF(100!), Y(3002), IA(360), AC(360)*PS(3002), X(360)
       6INTEG(6)
500 READ (5,299,END=999) ITD, ITM, ITS, NR
DO 499 I=1,3000
   Y(I) = 0
   AC(I) = 0
   PS(I) = 0
499 X(I) = 0
N=0
JSTORE = (360*ITH)+(60*ITM)+ITS-154
299 FORMAT (4I3,2IE)
300 FORMAT (A15)
301 FORMAT (12E10.3)
302 FORMAT (5X,3HDAY,15,5X,4HMOUR,14,5X,3MIN,14,5X,3HSEC,14)
303 FORMAT (3X,15HTIME GAP AT DAY,15,5X,4HMOUR,14,5X,3MIN,14,5X,
63HSEC,14)
   CALL PLOTS (IBUF,100C)
   CALL PLOT (0,,-11,-3)
   CALL PLOT (0,,-11,-3)
C BEGIN TIME SEARCH
1 READ (8,END=999) JDAY,JHR,JMIN,JSEC
   IF (JDAY*NE.1TD) Go TO 1
   IF (JHR*NE.ITH) Go TO 1
   IF (JMIN*NE.ITH) Go TO 1
   IF (JSEC*NE.ITS) Go TO 1
   BACKSPACE A
   CALL SYMBOL (1,0,9,C,2,12HDAY HR MIN,5,C,1C)
   CALL NUMBER (1,0,9,5,2,JDAY,14,C,-1)
   CALL NUMBER (1,0,9,5,2,JHR,14,C,-1)
   CALL NUMBER (1,0,9,5,2,JMIN,14,C,-1)
   DO 3C J=,1,NR
      READ (5,END=999) JDAY,JHR,JMIN,JSEC,IA,INTEG
51 JTIME=(3600*JHR)+(60*JMIN)+JSEC
   IF (((JTIME<JSTORE)+(LT,152)) Go TO 2C
   IF (((JTIME<JSTORE)+(LT,156)) Go TO 9
   PRINT 303, JDAY, JHR, JMIN, JSEC
   Go To 31
2C Do 21 IN=1,6
   IF (INTEG(IN) EO.3) Go TO 21
   IF (LN*NE.IN) Go TO 9
      Y(N) = Y(N) + INTEG(IN)
   LN=IN
   K=N+1
   IF (K*GT,6) Go TO 11
   Go To 22
21 CONTINUE
22 Do 23 IN=KN,6
   IF (INTEG(IN) EO.3) Go TO 21
   N=N+1
   Y(N)=INTEG(IN)
   LN=IN
23 CONTINUE
   ... GO TO 11
9   DO 10 IN=1,6
    IF (INTEG(IN).EQ.C) GO TO 10
    N=N+1
    Y(N) = INTEG(IN)
    LN=IN
10  CONTINUE
   ... JSTORE=JTIME
30  PRINT 302,JDAY,JHR,JMIN,JSEC
31  PRINT 300, N
    MAX=N/10
    PRINT 301,(Y(I),I=1,N)
C NORMALIZE DATA
   SUM=0
   DO 40 J=1,N
    SUM=SUM+Y(J)
    MEAN=SUM/N
   PRINT 300, MEAN
   SD=0
   DO 50 J=1,N
    Y(J)=Y(J)-MEAN
   SD=SD+Y(J)*Y(J)
   SD=SQRT(SD/N)
   PRINT 301, SD
   DO 60 J=1,N
70  Y(J)=Y(J)/SD
C CALCULATE AUTOCORRELATION FUNCTION
   LAG = C
65  SUM = 0
    DO 70 J=1,LAG+1
     SUM=Y(J)*Y(J+LAG)+SUM
     LAG=LAG+1
     AC(LAG) = SUM/(N-LAG+1)
    IF (LAG-MAX) 65,0,5,80
80  PRINT 301,(AC(I),I=1,MAX)
70  AC(I) = AC(I+1)
C CONVOLVE TO POWER SPECTRAL DENSITY
   LL=MAX-1
   DO 90 LAG=1,MAX
    PS(LAG)=0
   DO 85 L=1,LL
50  PS(LAG) = PS(LAG) + 2*AC(L)*(CCS(L,LAG-1,MAX))
   PS(LAG) = PS(LAG)+AC(MAX)*CCS(L,14,MAX)
   DO 100 L=1,MAX
100 X(I)=1
    CALL SCALE (X,1C,MAX,1)
    CALL SCALE (PS,9,MAX,1)
    CALL AXIS (0,0,0,22,FPOWER SPECTRAL DENSITY,9,9,4,4,PS(MAX+1),
6 PS(MAX+2))
    CALL AXIS (0,0,0,10,LAG NUMBER,-9,10...X(MAX+1),X(MAX+2))
    CALL LINE (X,PS,MAX+1,2,2)
    CALL PLOT (0,0,0,3)
    CALL PLOT (14,2,-3)
    REWIND H
   GC TO 5CC
999 STOP
END
APPENDIX A.4

C PARAM ALSEP/SIDE DATA MARTHA FENNER
C
C THIS PROGRAM ESTIMATES THE MAGNETOSPHERIC PARAMETERS AND CALCULATES THE
C KAPPA DISTRIBUTION FUNCTION FOR K=2 USING THE ESTIMATES OF BULK
C VELOCITY AND TEMPERATURE. NORMALIZATION OF THIS FUNCTION DETERMINES
C THE NUMBER DENSITY ON THE BASIS OF A TEST FOR GOODNESS OF FIT
C
C THE DISTRIBUTION FUNCTION IS ADJUSTED FOR A NEW TEMPERATURE
C AND A NEW KAPPA...
C
C NAVER = 0 INDICATES EACH SPECTRUM IS TREATED INDIVIDUALLY
C NAVER > 0 INDICATES THE NUMBER OF SIDE CYCLES AVERAGED
C
C THE ESTIMATED PARAMETERS AND PARAMETERS OF THE FIT ARE PLOTTED
C A 3-D DISPLAY OF THE DISTRIBUTION FUNCTION SPECTRA IS PLOTTED
C
C DIMENSION E(22), UNCKPS(22), EF(22), HI(22), VI(21), VELUNC(22), DF(22)
C 6DFVAR(22), OFUP(22), DFLG(22), KMSPEC(22), VS(22), CHISO(5)
C
C DIMENSION KEC(120), EK(21), JD(120), NEK(120)
C DIMENSION JA(120), KERGAR(120), NONE(120), ITER(120), INTEG(16)
C 1 JFLUX(120), JSTORE(120)
C DIMENSION TM(296), VEL(296), TEM(296), DEN(296), CAP(296), CHI(296)
C 6PRST(296), ENG(296), TF(296), TMM(296)
C DIMENSION BUF(100)
C
C DATA EM,20,30,50,70,100,225,500,750,1000,1250,
C 1 1500,1750,2000,2250,2500,2750,3000,3250,3500,3625/
C REAL KMSC, JINT, NERBAR, JFLUX, JAA, KK, KT, K1, KE
C
C COMPUTE THE SPEEDE AND VELOCITY PASS BAND
C
C DO 2 I = 1,21
C V(I)=13841.21287*SORT(E(I))
C VELUNC(1) = 346.03*SORT(E(I))
C KMSPEC(I) = V(I)/1000.
C 2 UNCKPS(I) = VELUNC(I)/1000.
C
C ISTOR=Z
C
C 1701 READ (5,178) EN=8001 IYEAR, INST
C 1702 FORMAT (2I4)...
C DO 700 I=1,20
C JFLUX(I)=0.C
C 700 EK(I)=EK(21-I)/10.
C
C PRINT HEADER
C PRINT 1776, IYEAR, INST
C 1776 FORMAT (10X,15.8 APODLO.14)
C PRINT 1779
C 1779 FORMAT (2X,20MCODE TO TYPE CF FIT,*,16M 1 = FIRST TRY,/
C 630H 2 = SECOND ESTIMATE T AND X FIT,/
C 626H 3 = MULTIPLE PEAK FIT,/
C 64X, 6HENERGY)
C PRINT 1780
C 1780 FORMAT (5X,3HDAY,4X,2HHR,3X,3HMIN,3X,4HFAVER,2X,11HTYPE OF FIT,4X,
C 56HCHISO,6X,6HVELOCITY,6X,4HTEMP,6X,5KHAPPA,4X,6HDENSTY,6X,4MTFIT,
C 64X, 6HENERGY)
C SEARCH FOR BEGINNING TIME
C NAVER=NUMBER OF CYCLES AVERAGED FOR ONE FIT, C MEANS TO FIT EACH SPECTRUM
C CNSPEC=NUMBER OF SPECTRA TO BE FIT
C
C 1777 FORMAT (9I3)
701 READ (5,1777,END=800) NDAY,NHR,NMIN,NAVER,NCALL,NDAY,NHR,NMIN
IFIT=2
C NAVER=0 CANNOT HANDLE DATA THAT IS ALL OUT OF TOLERANCE
C IF DIFF FLUX IS ZERO OR PARITY ERROR FOR ONE FRAME USE THE VALUE
C FROM THAT FRAME IN THE LAST CYCLE
KFIT=18
    IF (NAVER.GT.1) GO TO 1702
    IF (NAVER.EQ.0) GO TO 1704
LSIZE=IFIX(300./2.577)
GO TO 1703
1704 LSIZE=IFIX(360./2.577)
GO TO 1703
1702 LSIZE=IFIX(3000./(NAVER+2.577))
C NCALL IS THE NUMBER OF 50 HOUR PLOTS DESIRED
C NAVER IS THE NUMBER OF CYCLES OF DATA AVERAGED
C A CYCLE CONTAINING 6 SPECTRA
1703 JSPEC=0
PRINT 1800, IFIT,KFIT
1800 FORMAT (2X,29HTEMPERATURE IS ADJUSTED TO I+\,\,I/,2X, 
618HKAPPA IS FIT TO PT,13) 
MCALL = 0
ICALL=0
720 READ (1,END=830) JDAY,JHR,JMIN
    IF(NDAY.NE.JDAY) GO TO 720
    IF (NHR.NE.JHR) GC TO 720
    IF (NMIN.GE.JMIN) GC TO 720
BACKSPACE 1
901 KL=1
ML=0
    CALL PLOTS (IBUF,1000)
    CALL PLOT (0.0,-12.0,-3)
    CALL PLOT (0.0,12.0,-3)
C 5 DO 705 I=1,120
    NERBAR(I)=0
705 JA(I)=0
NISO=0
IFLAG=0
JINT=0
DO 707 I=1,20
797 H11=0.0
C C NOTE THAT INTEGRAL FLUX = INTEG * (10.**4)
C
    IF (NAVER.NE.0) GO TO 708
    IF (ISTOR.LT.6) GO TO 702
    ISTATE = 0
    READ (1,END=239) JDAY,JHR,JMIN,JSEC,(ISTORE(I),I=1,120), 
1INONE(1),I=1,120),(ITIME(1),I=1,120),(INTEG(1),I=1,6),NBG 
KDAY=JDAY
KHR=JHR
KMIN=JMIN
702 ISTATE=ISTATE+1
DO 703 J=1,20
M=(ISTORE-I)*20+J
L=21-J
IF (NONE(1) .EQ. 5) GO TO 5
IF (NONE(1) .EQ. 2) GO TO 703
IF (ISTORE(M) .GT. 0) GO TO 725.
ISTORE(M) = 0
NER(J) = 1
GO TO 703
******
725 KECT(J) = IFIX(ISTORE(M)/10000) * Ek(J) + NBG)
NER(J) = NBG + KECT(J) + (.0018 * (KECT(J) - NBG)**2)**4
******
726 JFLUX(L) = ISTORE(M)
703 NERBAR(L) = (NER(J))
JINT = INTEGRATOR
GO TO 771
******
708 DO 750 K=1, NAVE
IFLAG = 0
******
READ (1, END=239) JDAY, JHR, JMIN, JSEC, (JB(1), I=1, 120)
2(NONE(1), I=1, 120), (ITIME(1), I=1, 120), (INTEG(1), I=1, 16), NBG
IF (1, JDAY .LT. MDAY) GO TO 699
IF (JHR .LT. MHRA) GO TO 699
******
C PLOT WILL END WITH THE LAST COMPLETE AVERAGE SPECTRUM
GO TO 239
699 IF (K .GT. 1) GO TO 706
KDAY = JDAY
KHR = JHR
******
706 DO 711 L=1, 6
DO 710 M=1, 20
I = ((L-1)*20 + M)
IF (M .LT. 14) GO TO 787
RJB = FLOAT(JB(I))
REB = FLOAT(JB(I))
******
710 IF (NHB .GT. AJB .LT. 10000) JB(I) = 0
******
787 IF (JB(I) .GT. C) GO TO 722
JB(I) = C
KECT(I) = 0
GO TO 723
******
722 IF (NNB .EQ. 5) NBG = 0
******
KECT(I) = IFIX(JB(I)/10000) * Ek(M) + NBG)
723 IF (NONE(1) .EQ. 1) GO TO 710
IF (NONE(1) .EQ. 5) NDISO = NDISO + 6
IF (NONE(1) .EQ. 2) GO TO 710
IFLAG = IFLAG + 1
******
IFL(IG .EQ. 10). GO TO 710
IF (JBI .LT. 10000000) GO TO 710
JBI(1) = 0
******
710 CONTINUE
711 CONTINUE
DO 730 I = 1, 120
JAI(I) = JB(I) + JA(I)
******
730 NERBAR(I) = NERBAR(I) + KECT(I) + NBG + .0018 * ((KECT(I) - NBG)**2)**4
DO 715 I = 1, 6
JINT = JINT + INTEG(I)
******
750 CONTINUE
ANDNMC = NAVE + NDISO
DO 760 M = 1, 20
JAM(M) = JA(M) + JA(M+20) + JA(M+40) + JA(M+60) + JA(M+80) + JA(M+100)
780 NERBAR(M)=NERBAR(M)+NERBAR(M+Q)+NERBAR(M+10)+NERBAR(M+60)+
6 NERBAR(M+80)+NERBAR(M+100)
    DO 770 M=1,20
    L=21-M
    IF (JA(M).EQ.0.0) GC TO 769
    JFLUX(L)=JA(M)/NDENCM
    769 NERBAR(L)= (NERBAR(M)/NAVER*6)
    770 CONTINUE
    JINT=JINT/NDEGM
    C CALCULATE DISTRIBUTION FUNCTION (10KS/M**3/(M/SEC)**3)
    DO 780 I=1,20
      DF(I)=Q.54492/10**12*JFLUX(I)/E(I)
      DFVAR(I)=Q.2969387/10**14*(NERBAR(I))**E(I)**4
      SIGMA=SQRT(DFVAR(I))
    780 DFUP(I)=DF(I)+SIGMA
    10 DFDW(I)=DF(I)-SIGMA
    C ENERGY DENSITY ERGS/CM**3
    ENER=0.0
    DO 335 J=5,20
      ENER=ENER+DF(J)*V(J)**4*(V(J+1)-V(J-1))/2.
      ENERGY=ENER**0.786/10**20
    335 ENER=ENER+DF(J)*V(J)**4*(V(J+1)-V(J-1))/2.
    DO 345 J=12,20
      ENER=ENER+DF(J)*V(J)**4*(V(J+1)-V(J-1))/2.
      ENER2=ENER**0.786/10**20
      IF (ENER2.GT.0.0) GC TO 346
      ENERGY = 0.0
      GO TO 327
    346 ENERGY=ENER2/ENER
    C LOCK FOR MAXIMUM VALUE OF THE DISTRIBUTION FUNCTION (CHANNELS*GE*100EV)
    347 DFMX=0.
    DO 20 J=6,19
      IF(DFMX+GE*DF(J)) GC TO 20
      DFMX=DF(J)
    20 CONTINUE
    350 DMIN=5/10**9/E(I)
    IF (DFMX.LT.DMIN) GC TO 240
    61 IF(I-6)=240*62/63
    62 VBULK=V(I)
    C WE CANNOT DEAL WITH PEAKS AT 100EV EXCEPT TO PLOT V BULK AND IGNORE
    C OTHER PARAMETERS
    C IF (K>EQ+1) GO TO 240
    CHISQR = 0.0
    INDEX=5
    GO TO 200
    63 IF (I.GT.18) GO TO 240
    IFIRST=I-2
    IEND=12
    C ESTIMATE OF BULK VELOCITY (M/SEC)
    SUMNUM = 0.
    SUMDEN = 0.
DO 33 I=1,FIRST*;IEND
DELTAV = (V(IPTS+1) - V(IPTS-1))/2.
SUMNUM = SUMNUM + DF(IPTS) * V(IPTS) * DELTAV
33 SUMDEN = SUMDEN + DF(IPTS) * DELTAV
BULKV = SUMNUM/SUMDEN.
C ESTIMATE OF TEMPERATURE (X**5 DEG K)
34 VSQNUM = 0.
   VSQDEN = 0.
   DO 35 I=1,FIRST*;IEND
   DELTAV = (V(IPTS+1) - V(IPTS-1))/2.
   VSQNUM = VSQNUM + DF(IPTS) * ((V(IPTS) - BULKV)**2) * DELTAV
35 VSQDEN = VSQDEN + DF(IPTS) * DELTAV
   TEMP = 1.2153/10.**9*VSQNUM/VSQDEN
C ESTIMATE OF NUMBER DENSITY (ICNS/CM**3)
C ASSUME A 10 DEG CONE FOR FWHM OF FLOW
   DENSTY = INT/EULKV**5.4
C ESTIMATE OF ANGLE WRT BULK FLOW
   THEETA = 0.
C
   ITRY = 0
   CHIOLD = 2.0
C
   DO 40 J=1,2)
40 V(J) = V(J)**2 - 2.*V(J)*EULKV*COS(THEETA) + BULKV**2
   VBUKL = BULKV.
   INDEX = 1.
   NPKS = 0
C
   IF = IFIT
   KF = KFIT
C
   SECOND ESTIMATE I AND K.FIT
C
   71 I = I + 1
   IFIRST = 1
C
   72 RATIO = (DF(I)/DFMAX)***((1./3.)
   I2**(VS(I)**3**RATIO-VS(I)))/3.016/10.**8/(1.-RATIO).
   IF (T2**LE.0.0) GO TO 240
   SIG = (DFUP(KF) - DF(KF))**0.61
   CALL FITK (KK,T2,SIG,VS(KF),DFMAX,VS(I),DF(KF))
   NEMAX = DFMAX
   II = I
C
C
C KCTE KAPPA DISTRIBUTION
C
351 DO 341 J=1,2)
341 H(J) = 0.
C
   KT = KK-1.5
   KI = GAMMA(KK+1)/GAMMA(KT+1)
   TE = KK/KT*T2
   IF (T2**LE.0.0) GO TO 240
   DO 340 J=IFIRST,20
   VSQ = (V(J)**2 - 2.*V(J)*HULKV*COS(THEETA) + HULKV**2)
   H(J) = 2.677/10.**9*DENSTY/TE/SORT(TE)/(1.+VSQ /1.e51/1.**9/KT/2 TE )**(KK+1.))**K**1
340 CONTINUE
CNORMALIZE TO MAXIMUM FLUX
FAC=MEMAX/M(I)
IF (INDEX.EQ.1) DENSITY=FAC*DENSITY
354 DO 355 J=IFDEFIRST,20
355 M(J)=FAC*M(J)
359 CHISQR=0.
DO 366 J=6,20
  FF(J)=DF(J)-M(J)
IF (DFVAR(J).*LE.*0.0) GO TO 366
CHISQR=CHISQR + (FF(J)**2/DFVAR(J))
366 CONTINUE
CHISQR=CHISQR/11.
IF (CHISQR.LT.1) GC TO 200
INDEX=2
ITRY=ITRY+1
CHISQ(ITRY)=CHISQR
IF=IF+1
KF=KF+1
IF (ITRY.LT.5) GO TO 71
KEEP=5
DO 291 J=1,4
IF (CHISQ(J)+GT.CHISQR) GC TO 201
CHISQR=CHISQ(J)
KEEP=J
291 CONTINUE
IF (KEEP.EQ.5) GO TO 202
IF=IF+1
KF=KF - (KEEP-1)
III=I+1
RATIO=(DF(I)/DFMAX)**(1./3.)
T2=(VS(I)*RATIO-VS(I))/33*0.16/10.***8/(1-RATIO)
SIG=(DFUP(KF)-DF(KF))**0.5
CALL FITK (KK+T2+SIG,VS(KF),DFMAX,VS(I),DF(KF))
202 IF (CHISQR.LT.10) GO TO 200
KK=0.0
CHISQR=10.5
GO TO 200
239 LSIZE=KL
GO TO 250
C NC SPECTRUM PRESENT GT 100EV
240 CHISQR=0.0
241 VBUKL=100000.
242 T2=C+0
TEMP=0.0
DENSITY=0
INDEX=0
KK=0.0
C C BEST FIT HAS BEEN FOUND, READY FOR OUTPUT
C C
C REDUCED CHI SQUARE
200 CONTINUE
CALL PLT3D (KDAY,KHR,KMIN,KMSEC,DF,XI,YI,MCALL,LSIZE,IYEAR,
61NS,NAVER).
BUKL=VBUKL
PRINT 255,KDAY,KHR,KMIN,NAVER,INDEX,CHISQ,BUML,T2,ENERGY
255 FORMAT (2X,5I6,E16.2,E15.3,E10.3,E10.3)
IF (DENSTY*GT.*15.) DENSTY=15.0
IF (KK*GT.*60.) KK=60.
IF (TEMP*GT.*20.) TEMP=20.0
IF (T2*GT.*35.) T2 = 35.0
IF (CHISOR*GT.*10.) CHISOR=10.5
250 PRES = 1.3804 #10. #DENS11*TEMP
IF (PRES*LE.*0.) PRES=1.0
PRES=1.0#ALOG10(PRES)
CALL OUTPUT (KL,NDAY,NHR,KDAY,KMR,KMIN,BULKV,TEMP,DENSTY,KK,
0.5CHISOR*T2,TIM,VEL,TEN,DEN,KAP,CH1,PRST1,ICALL,NMIN,YEAR,INST,
ENERGY,SIZE,ML,TIM,W,NAVER)
WHITE (2,END=800) KDAY,KMR,KMIN,PRES,KK,DENSTY,VBULK,TEMP,ENERGY,
6CHISOR,OF(1),IF=1.20)
599.1SPEC=1SPEC+1
600 IF (ICALL.LT.NCALL) GO TO 5
GO TO 1201
C
800 STOP
END

SUBROUTINE FITK (C,TEMP,SIG,VO,DFMAX,VS1,DATA)
C
C THIS SUBROUTINE FITS K TO THE HIGH ENERGY TAIL
C
C
C=1.5
DELTA=.1
TEST1=1.
DO 50 I=1,550
C = C + DELTA
CT=C-1.5
IF (CT*LE.*0.) GO TO 80
TE=C/CT*TEMP
IF (VS1*LE.*0.) GO TO 90
IF (VO*LE.*0.) GO TO 90
CAPP=DFMAX*(1+VS1/1.651/10.**9/CT/TE)/
2*(1+VO/1.651/10.**9/CT/TE)**(C+1)
TEST2 = CAPP/DATA
PROD = TEST1*TEST2
IF (PROD*GT.*0.0) GO TO 40
DELTA = -0.1*DELTA
40 TEST1=TEST2
IF (ABS(TEST2).LT.SIG) GC TC 90
50 CONTINUE
GO TO 90
80 C=1.6
90 RETURN
END
SUBROUTINE OUTPUT (KL, NDAY, KHR, KDAY, KMIN, VEL1, TEM1, DEN1, 
6CAP1, CHI1, T2, TIM, VEL, TEM, DEN, CAP, CHI, PHS, TFI, CALL, NMIN, IYEAR, 
6INST, ENERGY, ML, TIMM, NAVER) C
C THIS SUBROUTINE ACCUMULATES THE DATA FOR N HOURS. 
C THEN PLOTS THE PARAMETERS IN TWO PLOTS
C IF NAVER = 0, N = 5
C IF NAVER > 0, N = 50.
C SUBMIT SEPARATE DATA CARD FOR EACH N HOUR PLOT
C
DIMENSION TIM(296), VEL(296), TEM(296), DEN(296), CAP(296), CHI(296), 
6PHS(296), TFI(296), TIMM(296)
IF (KL > GT + 1) GO TO 15
NDAY = KDAY
NHR = KHR
KMIN = KMIN
15 VEL(KL) = VEL1 / 1000.
TEM(KL) = TEM1
DEN(KL) = DEN1
TIM(KL) = (KDAY - NDAY) * 24 + (KHR - KMIN) * NMIN / 60.
IF (CHI1 > GE + 2.0) GO TO 10
ML = ML + 1
CAP(ML) = CAP1
TFI(ML) = T2
TIMM(ML) = TIM(KL).
10 ENGI(KL) = ENERGY
IF (CHI1 > GE + 5.0) CHI1 = 5.0
CHI(KL) = CHI1
IF (KL = L + 1) GO TO 100
CALL PARAX (NDAY, KHR, KMIN, IYEAR, INST, NAVER)
TIM(L + 1) = 0.
IF (NAVER = EQ = 0) TIM(L + 2) = 2.
IF (NAVER = EQ = 1) TIM(L + 2) = 1.
IF (NAVER = GT = 1) TIM(L + 2) = 10.
VEL(L + 1) = 100.
VEL(L + 2) = 4000.
TEM(L + 1) = 0.
TEM(L + 2) = 20.
TFI(ML + 1) = 0.0
TFI(ML + 2) = 20.0
TIMM(ML + 1) = 0.
TIMM(ML + 2) = 10.0
DEN(L + 1) = 0.
DEN(L + 2) = 12.
CAP(ML + 1) = 0.
CAP(ML + 2) = 40. / 1.5
CHI(KL + 1) = 0.
CHI(KL + 2) = 4.
PHS(L + 1) = 0.
PHS(L + 2) = 3.
ENGI(L + 1) = 0.
ENGI(L + 2) = 1. / 1.5
CALL LINE (TIM, DEN, L + 1, 6, 0)
CALL PLOT (8.5, 0.0, -3)
CALL LINE (TIM, CHI, L + 1, 0.0)
CALL PLOT (0.0, 1.0, 0.0, -3)
CALL LINE (TIM•ENG•L•1•0•0)
CALL PLOT (0•0•1•9•-3)
CALL LINE (TIM•TFI•ML•1•0•0)
CALL PLOT (-4•0•0•0•-3)
CALL PLOT (-4•5•-2•0•-3)
CALL LINE (TIM•VEL•L•1•0•0)
CALL PLOT (-5•0•1•75•-3)
CALL LINE (TIM•TFM•L•1•0•0)
CALL PLOT (0•0•1•25•-3)
CALL LINE (TIM•ENG•L•1•0•0)
CALL PLOT (3•0•1•75•-3)
CALL LINE (TIM•PRR•L•1•0•0)
CALL PLOT (5•5•-25•-3)
CALL LINE (TIM•CAP•ML•1•0•0)
I CALL=ICALL+1
RATIO=ML*100./KL
PRINT 120, RATIO
120 FORMAT (F10.3,3SH PERCENT OF DATA USED IN KAPPA FIT)
CALL PLOT (0•0•-5•5•-3)
CALL NUMBER (4•0•-8•1•HATIC•0•1)
CALL SYMBOL (4•5•-2•1•HATIC•0•1)
CALL SYMBOL (4•0•-1•0•+1.9•CHISQR <2.5•C•5)
CALL PLOT (6•1•0•0•3)
CALL PLOT (0•1•0•5•2)
CALL PLOT (8•5•-12•0•-3)
KL=0
ML=0
100 KL=KL+1
RETURN
END
SUBROUTINE PLT30 (KDAY, KHR, KMIN, KMPSEC, DF, XI, YI, MCALL, L, YEAR, 6INST, NAVER)

C
C THIS SUBROUTINE DRAW A 3-C PLOT OF DISTRIBUTION FUNCTION SPECTRA
C IF NAVER = 0 IT PLOTS 5 HOURS OF DATA
C IF NAVER > 0 IT PLOTS 50 HOURS OF DATA
C
C DIMENSION IBUF(1000), XARRAY(23), YARRAY(23), KMPSEC(22), DF(20)
REAL KMPSEC
IF (MCALL .NE. 0) GC TO 36
XI = 0.0
YI = 0.0
CALL PLOT (0.0, -12.0, -3)
CALL PLOT (0.0, +12.0, -3)
C DRAW VELOCITY AXIS
CALL PLOT (XI, YI, 3)
DO 10 I = 1, 3
CALL PLOT (XI + I, YI, 2)
CALL PLOT (XI + I, YI - 0.5, 2)
10 CALL PLOT (XI + I, YI, 2)
MODU = 24
LIM = 5.
IF (NAVER .NE. 0) GO TO 13
LIM = 0
C MODU = 60
13 DO 11 I = 1, LIM
X = XI + 3.0 * 3712 * I / LIM
Y = YI + 928 * I / LIM
CALL PLOT (X, Y, 2)
CALL PLOT (Y, X, 2)
CALL PLOT (X, Y, 3)
DO 12 I = 1, LIM
Y = YI + 928 * I / LIM - 0.5
X = XI + 3.0 * 3712 * I / LIM + 0.5
IF (NAVER .EQ. 0) IHR = KMIN + 10 * I
IF (NAVER .EQ. 1) IHR = KHR + I
IF (NAVER .GT. 1) IHR = KHR + I * 10
AMHR = MOD(IHR, MODU)
12 CALL NUMBER (XI + AX, YI + 15, 1, AN + 0.0, -1)
CALL SYMBOL (XI + 15, YI + 3.0, 3, 9HTIKE (LT), 68.1, 9)
DO 20 I = 1, 3
AX = 3.85 - I / 3.
AN = 12000 - I * 300
20 CALL NUMBER (XI + AX, YI + 15, 1, AN + 0.0, -1)
CALL SYMBOL (XI + 25, YI + 4, 15, 10HV (KMPSEC), 66.1, 10)
C DRAW Y AXIS
CALL PLOT (XI, YI, 3)
DO 30 I = 1, 9
YI = YI + 1.0
CALL PLOT (XI, YI, 2)
CALL PLOT (XI - 0.5, YI, 2)
30 CALL PLOT (XI, YI, 2)
DO 31 J = 1, 9
X = XI + 3.0 * 3712 * J
Y = YI + 928 * J
CALL PLOT (X, Y, 2)
CALL PLOT (X, Y, Z, 2, 2)

31 CALL PLOT (X, Y, Z)
   DO 35 I=1, 4
   AN=-3, -1, 3
   Y1=(4*I/12.05)
35 CALL NUMBER (XI=3.5, YT=1, AN, C, 0, -1)

CAXIS, LABEL
   CALL SYMBOL (XI=3.5, Y1=1, 29, HLCG DISTRIBUTION FUNCTION (V1), 90, 29)
CWRITE DATE AND TIME OF FIRST DATA PT IN AVERAGE
DAY=DAY
T6=KHR
TMIN=KMIN
YEAR=YEAR
HNST=INST
   CALL NUMBER (XI=3.5, YEAR, 3, 0, -1)
   CALL SYMBOL (XI=3.5, c=8.16, HLCG DISTRIBUTION FUNCTION (V1), 90, 6)
   CALL NUMBER (XI=3.5, TIMER, 0, 0, -1)
   CALL SYMBOL (XI=3.5, C, 1, 3, HLCG DISTRIBUTION FUNCTION (V1), 90, 3)
   CALL NUMBER (XI=3.5, 1, Q, 1, DAY, 3, 0, -1)
   CALL SYMBOL (XI=3.5, 1, Q, 1, DAY, 3, 0, -1)
   CALL NUMBER (XI=3.5, 1, Q, 1, HNC, 0, 0, -1)
   CALL SYMBOL (XI=3.5, 1, Q, 1, HNC, 0, 0, -1)
   CALL NUMBER (XI=3.5, 1, Q, 1, HNC, 0, 0, -1)
   CALL PLOT (0, 7, 0, 0, 3)
   CALL PLOT (4, 1, 0, 2)

C
C PLOT DATA
   XI=XI+3.8*146/L
   YI=IY+K6*146/L
   DO 40 K=1, 20
   XARRAY(K)=KMBEC(K)*XI
   IF (DF(K), LT, 1.0*15) DF(K)=1.0*15
   40 YARRAY(K)=ALOG10(DF(K)) + YI
   XARRAY(21) = 900 + XI
   XARRAY(22) = 900 + XI
   XARRAY(23) = 900 + XI
   YARRAY(21) = -15 + YI
   YARRAY(22) = -15 + YI
   YARRAY(23) = -15 + YI
   CALL LINF (XARRAY, YARRAY, 21, 1, 0, 0)
   MCALL = MCALL + 1
   IF (MCALL, LT, L) GO TO 70
   MCALL = 20
   70 RETURN
END
SUBROUTINE PAREX (NDAY, NHR, NMIN, IYEAR, INST, NAVEP)

   THIS SUBROUTINE DRAWS THE AXIS OF THE PARAMETER PLOTS
   TWO PLOTS ARE DRAWN SIMULTANEOUSLY FOR THE SAME DATA

   IF NAVEP=0 THE SCALE IS ONE HOUR = ONE INCH
   IF NAVEP>0 THE SCALE IS 10 HOURS = ONE INCH

DIMENSION IBUF(1001)
CALL PLOTS (IBUF,1000)
INDEX=1
XI=0.0
CALL PLOT (0.1,0.0,3)
CALL PLOT (0.2,0.0,6)
CALL PLOT (0.3,0.5,3)

DRAW THE TIME AXIS

DAY=NDAY
HR=NHR
MMIN=NMIN
YEAR=IYEAR
INST=INST

5 CALL PLOT (XI,0.0,3)
   IF (NAVEP.NE.0) GC TO 6
   DO 7 I=1,6
      AI=I*XI/6
      INMIN=NMIN+10*I
      AMR=MOD(INMIN,60)
      CALL PLOT (AI,0.0,2)
      CALL PLOT (AI,0.0,2)
      CALL NUMBER (AI-.09, -25, 1, AMR,.0,.0,-1)
    7 CALL PLOT (AI,0.0,3)
   GO TO 11

6 DO 10 I=1,9
   AI=I*XI
   IF (NAVEP.EQ.1) IMH=NHR+1
   IF (NAVEP.EQ.1) HRH=NHR+10
   AMR=MOD(IMH,24)
   CALL PLOT (AI,0.0,2)
   CALL PLOT (AI,0.0,2)
   CALL NUMBER (AI-.03, -25, 1, AMR,.0,.0,-1)
10 CALL PLOT (AI,0.0,3)

11 CALL SYMBOL (XI+1.5,-5,15.0TIME (UT).C,0,.5)
   CALL NUMBER (XI-.05,1,YEAR,.0,.0,1)
   CALL SYMBOL (XI-.5,-6,.16APOLLN.0,.0,.0)
   CALL NUMBER (XI1+.2,0,.1,HINST,.0,.0,1)
   CALL SYMBOL (XI1-.1,.3.0,.0,.0,.0,.0,.0)
   CALL NUMBER (XI1+.4,-1,0,.1,DAY,.0,.0,-1)
   CALL SYMBOL (XI1+.3,1,0,.1,2HR,.0,.0,.0)
   CALL NUMBER (XI1-.2,1,0,.1,HRR,.0,.0,-1)
   CALL SYMBOL (XI1+.5,1,0,.1,3MIN,.0,.0,.0)
   CALL NUMBER (XI1+.9,1,0,.1,HMIN,.0,.0,-1)
   IF (INDEX.EQ.2) GC TO 20
INDEX=2
XI=0.5
CALL PLOT (6.1,0.0,3)
CALL PLOT (6.1,0.5,2)
GO TO 5

C DRAW FIRST Y AXIS

25 CALL YAXE (0.0,0.0,1.25,6.0,0.3,0)
CALL SYMBOL (-.5,.01,.01,12,DEN (CM**-3),9C*,12)
CALL YAXE (0.01,1.5,1.01,100,*100)
CALL SYMBOL (-.5,1.5,.10,.17MBULK VEL (KM/SEC),9C*,17)
CALL YAXE (0.53,3.25,2.5,0.5,0.5,1)
CALL SYMBOL (-.5,5.25,.01,11H(10**5 DEG),9C*,11)
CALL YAXE (0.04,4.5,1.5,5,.01,25)
CALL SYMBOL (-.5,4.6,.01,12HEnergy RATIO,9C*,12)
CALL YAXE (0.06,6.25,1.3,4,-12,.01,1)
CALL SYMBOL (-.5,6.25,1.11MC LC CY1/2G,9C*,11)

C DRAW SECOND Y AXIS

CALL PLOT (4.1,0.0,3)
CALL YAXE (8.5,0.0,1.25,6.0,0.1,0)
CALL SYMBOL (9.0,1.0,10,MCHI SQUARE,9C*,10)
CALL YAXE (8.5,1.6,1.5,5,.01,25)
CALL SYMBOL (8.0,1.2,12HEnergy RATIO,9C*,12)
CALL YAXE (8.5,3.5,1.75,5,.01,5)
CALL SYMBOL (8.0,3.5,1.16,TFIT (10**5 DEG),9C*,16)
CALL YAXE (8.5,5.5,1.5,5,.01,10,)
CALL SYMBOL (8.0,5.5,1.15,HEAT (HE TAIL),9C*,15)

BORDER

CALL PLOT (7.6,7.5,3)
CALL PLOT (13.6,7.5,2)
CALL PLOT (13.6,9.1,2)
CALL PLOT (7.6,9.1,2)
CALL PLOT (7.6,7.5,2)
CALL PLOT (5.1,7.5,3)
CALL PLOT (5.1,9.1,2)
CALL PLOT (-0,9.7,5,2)
 CALL PLOT (5.1,7.5,2)
RETURN
END

SUBROUTINE YAXE (XI,BEGI N,YLEN,NDIV,FIRST,DEL)

C THIS SUBROUTINE ANNOTATES THE Y AXIS FOR A SINGLE PARAMETER

C

SC=YLEN/(NDIV-1)
CALL PLOT (XI+BEGI N,1)
CALL PLOT (XI+YLEN+BEGI N,2)
DO 10 I=1,NDIV
AI=(I-1)*DEL + FIRST
BI = (I-1)*SC + BEGI N
CALL PLOT (XI,81,3)
CALL PLOT (XI+CHI,81,2)
CALL PLOT (XI+81,81,3)
10 CALL NUMER (XI,4,BI-.05,.1,81,0,0,1)
RETURN
END
APPENDIX A.5

C TEDIT ALSEP-SIDE DATA
C TEDIT IS A PROGRAM WHICH USES THE PENNER EDIT TAPES TO PLOT A 10 MINUTE C
C RUNNING AVERAGE OF INTEGRAL FLUX OR PEAK ENERGY ON THE BENSON LEHNHA
C USE 2ND DIGIT OF WORD 2 FOR X AXIS - ACCUMULATED TIME IN SECONDS C
C THE PLOTTER CONTROLS CAN BE SET FOR A SCALE OF 10 HOURS = 1 INCH
C USE 3RD WORD FOR ANNOTATION C
C USE WORDS 5 TO 9 FOR Y AXIS
C WORD 5 = INTEGRAL FLUX OF A SINGLE SPECTRUM
C WORD 6 = ENERGY CHANNEL FOR WHICH DIFFERENTIAL FLUX IS A MAXIMUM
C WORD 7 = BACKGROUND COUNTING RATE
C WORD 8 = 10 MIN RUNNING AVERAGE OF INTEGRAL FLUX (USING 24 SPECTRA)
C THE AVERAGE OF THE PREVIOUS 10 MINUTES, CALCULATED AFTER
C EACH COMPLETE SIDE CYCLE, IS PLACED IN ALL 6 FRAMES
C
C WORD 9 = THE SAME RUNNING AVERAGE PERFORMED ON THE PEAK ENERGY
C ONE PAGE PRINTOUT CONTAINS ONE HUNDRED HOURS OF DATA
C ONE OUTPUT TAPE CONTAINS ONE HUNDRED HOURS OF DATA
DIMENSION KECT(120),IFLAG(120),ITIME(120),INTEG(6),
6KC1(120),MPA(6),ISTORE(24),MSTORE(24),IE(25)
DATA IE=3500,3250,3000,2750,2500,2250,2000,1750,1500,1250,1000,
6750,500,250,100,50,30,20,10
JJ = 0
ITIME(1)=0
ITIME(21)=0
ITIME(41)=0
ITIME(61)=0
ITIME(81)=0
NSUM=0
KONST=0
N=0
DO 601 IE=1,24
MSTORE(IE)=0
601 MSTORE(IE)=0
NPL=0.
800 READ (5,3,END=998) IDAY, IHR, IMIN, NDAY, NH, NM, NSKIP
3 FORMAT (213,12,1X,213,12,14)
IAVER = 0
MEVER = 0
801 READ (8,END=999) IDAY, JHR, JMIN, JSEC
C BEGIN SEARCH
IF (IDAY .NE. JDAY) GC TO 801
802 IF (IHR .NE. JHR) GC TO 801
803 IF (IMIN .GT. JMIN) GC TO 801
BACKSPACE B
NB=-500
MEN=-500
IA=-500
MEA=-500
INT=-500
ITEIN=0
IZZ=800000
C USE ANNOTATION WORD =3 FOR JCAY
C WORD 4 CONTAINS BOTH JHR AND JMIN
WRITE (9,100) IZZ, ITEIN, JDAY, JHR, JMIN, INT, MEN, NA, IA, ME
STH=JHR
NB=-500
MEN=-500
IA=-500
MEA=-500
INT=-500
ITEIN=0
IZZ=800000
C USE ANNOTATION WORD =3 FOR JCAY
C USE WORD 4 CONTAINS BOTH JHR AND JMIN
WRITE (9,101) IZZ, ITEIN, JDAY, JHR, JMIN, INT, MEN, NA, IA, ME
STH=JHR
NB=-500
MEN=-500
IA=-500
MEA=-500
INT=-500
ITEIN=0
IZZ=800000
WRITE (9,100) IZZ, ITEIN, JDAY, JHR, JMIN, INT, MEN, NA, IA, ME
IZZ=34000
WRITE (9,100) IZZ, ITEIN, JDAY, JHR, JMIN, INT, MEN, NA, IA, ME
PRINT 205, JDAY, JHR, JMIN, JSEC
LT=JSEC+60*JMIN
10 READ (8,END=999) JDAY, JHR, JMIN, JSEC, (KECT(I), I=1,120),
   6(FLAG(I), I=1,120), (ITIME(I), I=1,120), INTEG, NBG
11 IZZ=80000
12 DO 50 I=1,6
   50 K=1-I
   IF (ITIME(I)+20*K+1) GT 0 GO TO 30
   ITIME(I)+20*K+1=LT*2A =KONST
   IF (FLAG(K+20)*EC=0) ITIME(I+20)=0
30 GO 20 K=1+20
   IF (FLAG(K+20)*LT*6) GO TO 16
   IF (FLAG(K+20)*GT*6) GO TO 200
   IF (ST*GT*0) GO TO 33
   KONST=KONST+3600
   N=N+1
   GO TO 32
33 READ (8,END=999) JDAY, JHR, JMIN
   BACKSPACE 8
298 N=(JHR-STH) 298*6.300
299 N=(JHR+2A-STH),
   GO TO 301
300 N=JHR-STH
301 KONST=N*3600
32 IF (N+LT*10) GO TO 16
   GO TO 201
C FOR BLOTS >10 HOURS OR HV OFF, WE LCSE ONE SPECTRUM OR ONE INTEG POINT
CALT MARK WHEN HV HAS BEEN OFF
200 READ (8,END=999) JDAY, JHR, JMIN, JSEC
   BACKSPACE 8
   PRINT 560
500 FORMAT (23MDISCNTINUOUS DATA MARK)
201 IZZ=80000
   WRITE (9,100) IZZ, ITIME(I+20), JDAY, JHR, JMIN, INTEG(I), PFEAK(I),
   INB, NAVE, NAVE,  
   KCHST=0
   N=0
   ITEIM=0
   INT=-550
   MEN=-500
   NB=-500
   IA=-500
   MEA=-500
   STH=JHR
25 IZZ=80000
   WRITE (9,100) IZZ, ITEIM, JDAY, JHR, JMIN,
   INT, MF, NB, IA, MEA
   INT=-750
   MEN=-750
   NB=-750
   IA=-750
   MEA=-750.
   WRITE (9,111) IZZ, ITEIM, JHR, JMIN, JDAY,
   INT, MEN, NB, IA, MEA
   IZZ=30000
   WRITE (9,100) IZZ, ITEIM, JDAY, JHR, JMIN,
   INT, MEN, NB, IA, MEA
   IZ=80000
202 PRINT 200, JDAY, JHR, JMIN, ITIME(K+20), IFLAG(K+20)
205 FORMAT (5(I6)
   LT=0
   GO TO 50
16 ITIME(K+20) = ITIME(K+20) + KCHST
20 CONTINUE
   MEN=0
C THE LOG OF THE INTEGRAL, MULTIPLIED BY 1000 IS KCA THE OUTPUT TO BE
C. PLUGGED ON THE TEXACO PLOTTEN
C BASE LINE OF INTEGRAL PLOTT IS 1000C
IF (INTEG(M+1) .LE. 0) GO TO 97
IF (INTEG(M+1) .LT. 100000) GO TO 98
DO 99 I = 1, 20
IF (IFLAG(M+20+1), EQ, 21) GO TO 49
99 CONTINUE
GO TO 98
97 INTEG(M+1) = 0
ISITORE(JJ+6+1) = 0
GO TO 95
98 AINT = FLOAT(INTEG(M+1))
ISTORE(JJ+6+1) = INTEG(I)
INTEG(M+1) = (ALOG10(AINT))*1000,
C ROUTINE TO CALCULATE THE PEAK ENERGY
95 MX = KECT(1+M+20)
ME = 100
DO 151 K = 2, 14
IF (MX, GT, KECT(K + M+20)) GO TO 151
MX = (KECT(K + M+20))
ME = K+100
151 CONTINUE
MPEAK(M+1) = 2000-ME
MSTORE(JJ+6+1) = IEIME/1000
96 WRITE(9, 100) IZZ, ITIME(1+M+20), JDAY, JHR, JMIN, INTEG(I), MPEAK(I),
6NBG, IAVER, MEAVER
49 LT = ITIME(1+M+20)
50 CONTINUE
C RUNNING AVER OVER 4 SIDE CYCLES
JJ = JJ+1
IF (JJ .EQ. 4) JJ = 0
ISUM = 0
150 DO 70 K = 1, 24
ISUM = ISUM + ISTORE(K)
70 MSUM = MSUM * MSTORE(IK).
IAVER = ISUM/24
MEAVER = MSUM/24
IF (IAVER .LE. 0) GO TO 71
AINT = FLOAT(IAVER).
IAVER = (ALOG10(AINT))*1000,
C END SEARCH
71 IF (NCAY .LT. JDAY) GO TO 10
IF (NHR .LT. JHR) GO TO 10
IF (NMIN .LE. JMIN) GO TO 10
IZZ = 000000
WRITE (9, 100) IZZ, ITIME(JDAY, JHR, JMIN), INT, MEN, NB, IA, MEA
999 END FILE 9
PRINT 997
997 FORMAT (2X, 17HEAD OF INPUT FILE)
998 STOP
END
APPENDIX A.6
Calculation of $\theta$ and $N$ Using 2 Instruments

1) For a single point in time, choose the 2 instruments having the largest counting rates. In order to use the data from both instruments to calculate the macroscopic parameters $\theta$ and $N$ independently of one another, the following assumptions must be made:

   a) That the phenomenon being observed extends uniformly to include both the ALSEP sites.

   b) That the effect of local magnetic and electric fields is known and can be accounted for in the calculations, and

   c) That the relative responses of the two instruments has been accurately measured so that their sensitivities can be normalized in the calculations.

2) Calculate the distribution function spectrum for each instrument. Adjust these 2 spectra to account for local field effects and the normalization of the sensitivities of the 2 instruments. Estimate a value of temperature and bulk velocity from each spectrum. Use the averages of these values ($T$ and $V_B$) in the equations below.

3) Solve simultaneous Maxwellian distribution function equations for $N$ and $\theta$. 
Write the equations such that angles are given with respect to reference line A or B (the mid-line between the look directions of a given pair of instruments). The resulting angle \( \theta \) should later be transformed so that it is given with respect to a reference parallel to the eath-sun line.

An example using reference line B:

\[
\begin{align*}
 f_{\text{max}_{14}} &= N\left(\frac{m}{2\pi kT}\right)^{3/2} \exp\left[\frac{-m\left(V_{\text{max}_{14}}^2 - 2V_{\text{max}_{14}} V_B \cos(\theta - 10^{\circ}) + V_B^2\right)}{2kT}\right] \\
 f_{\text{max}_{15}} &= N\left(\frac{m}{2\pi kT}\right)^{3/2} \exp\left[\frac{-m\left(V_{\text{max}_{15}}^2 - 2V_{\text{max}_{15}} V_B \cos(\theta + 10^{\circ}) + V_B^2\right)}{2kT}\right]
\end{align*}
\] (1)

Solve for \( \theta \)

\[
\begin{align*}
 f_{\text{max}_{15}} &= f_{\text{max}_{14}} \exp\left[\frac{-m}{2kT}\left(-V_{\text{max}_{14}}^2 + 2V_{\text{max}_{14}} V_B \cos(\theta - 10^{\circ}) + V_{\text{max}_{15}}^2 - 2V_{\text{max}_{15}} V_B \cos(\theta + 10^{\circ})\right)\right] \\
-\frac{2kT}{m} \ln \left(\frac{f_{\text{max}_{15}}}{f_{\text{max}_{14}}}\right) &= V_{\text{max}_{15}}^2 - V_{\text{max}_{14}}^2 + 2V_B \left(V_{\text{max}_{14}} - V_{\text{max}_{15}}\right) \cos 10^{\circ} \cos \theta \\
&\quad + \left(V_{\text{max}_{14}} + V_{\text{max}_{15}}\right) \sin 10^{\circ} \sin \theta
\end{align*}
\]
this reduces to the simple equation

\[ A \cos \theta + B \sin \theta = C \]

where

\[ A = 2V_B (v_{\text{max}14} - v_{\text{max}15}) \cos 10^\circ \]

\[ B = 2V_B (v_{\text{max}14} + v_{\text{max}15}) \sin 10^\circ \]

\[ C = \frac{2kT}{m} \ln \left( \frac{f_{\text{max}15}}{f_{\text{max}14}} \right) + \frac{v_{\text{max}14}^2}{2} - \frac{v_{\text{max}15}^2}{2} \]

This equation can be solved analytically:

\[ \theta = \sin^{-1} \left( \frac{C}{\sqrt{A^2 + B^2}} \right) - \tan^{-1} \frac{A}{B} \tag{3} \]

Putting the solution for \( \theta \) into either of the equations (1) or (2) and solve for \( N \).

\[ N = f_{\text{max}14} \left( \frac{2\pi kT}{m} \right)^{3/2} \exp \left[ \frac{m(v_{\text{max}14}^2 - 2v_{\text{max}14}V_B \cos(\theta - 10^\circ) + V_B^2)}{2kT} \right] \tag{4} \]
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