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SOME CONTRIBUTIONS TO KNOWLEDGE OF THE MAGNETOSPHERIC PLASMA BY ISEE INVESTIGATORS

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SOME CONTRIBUTIONS TO KNOWLEDGE OF THE MAGNETOSPHERIC PLASMA BY ISEE-1 INVESTIGATORS

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ABSTRACT

The ISEE project has made substantial contributions to our knowledge of the magnetosphere during the period of the IMS, especially in the discipline of Space Plasma Physics. This paper reviews results obtained during approximately the first two years of the operation of ISEE-1 and -2, and touches on relevant results of ISEE-3. The ability to control the separation between ISEE-1 and -2, which are in nearly identical orbits, has permitted study of the motion and structure of the bow shock and magnetopause, the boundary layers, and the plasma sheet. Much evidence has been obtained favoring the existence of reconnection and its relevance to the transfer of magnetic flux from the frontside to the rear of the magnetosphere, although not everyone agrees that it is the only important process. The presence of both reflected and accelerated particles has been shown to lead to the development of a foreshock region between the bow shock and the interplanetary magnetic field line tangential to it. In an analogous development, precursors to interplanetary shocks have also been observed. Inside the magnetosphere, ISEE has contributed to our knowledge of plasma waves, and, augmenting work with GEOS, to studies of plasma composition. In the near tail, the boundary layer of the plasma sheet has disclosed interesting phenomena. This progress has largely resulted from the improvement of time resolution, and other development of the measurement techniques involved rather than from cooperative research involving more than one spacecraft. Thus much new material awaits discovery and exploitation.

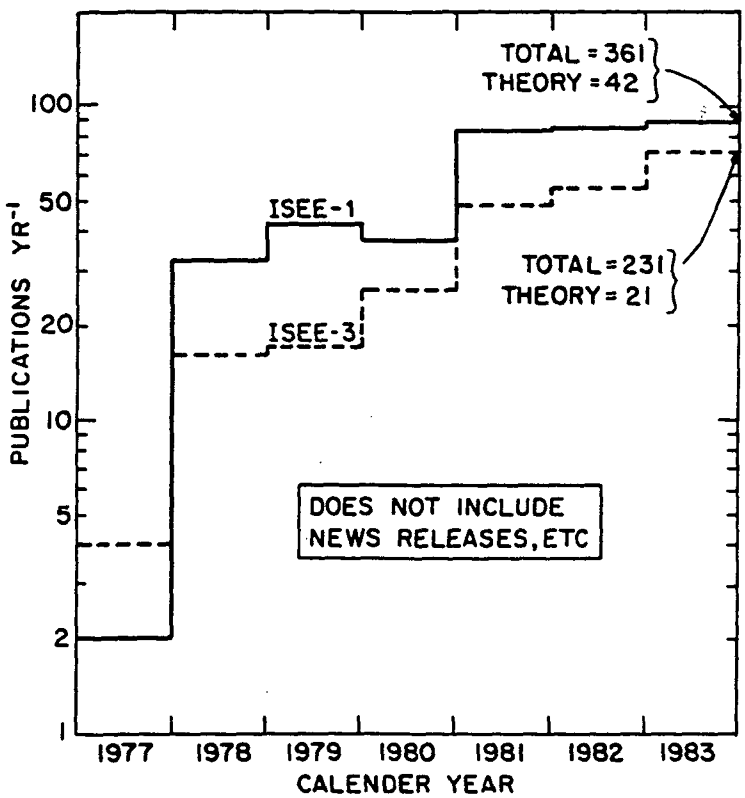
Key Words: ISEE, Magnetosphere, Reconnection

1. INTRODUCTION

The idea of using two spacecraft close to one another in the same eccentric orbit as a means to study the structure and motions of the essential magnetospheric boundaries, bow shock, magnetopause, plasma pause, plasma sheet, etc., originally came from F. McDonald, and was developed in a comprehensive report "Mother-Daughter Satellite Systems Feasibility Study" produced in 1969 (Ref. 1). This and other studies also provided a requirement and rationale for upstream solar wind and cosmic ray observations by a spacecraft - ISEE-3 - which was to be maintained in a halo orbit about the forward libration point. NASA and ESA joined forces and decided that the "mother" spacecraft, ISEE-1, would be built by NASA at GSFC, and that ESA would have the smaller ISEE-2 built in Europe although they would use the same launch vehicle. A joint selection in 1972 produced an international payload covering all 3 spacecraft of 31 instruments from over 80 proposals, and the Science Working Team began reviewing the plans for the mission in detail. The instruments are described in a special issue of Geoscience Electronics (1978). ISEE-1 and -2 were launched in August 1977, and ISEE-3 in October 1978 and

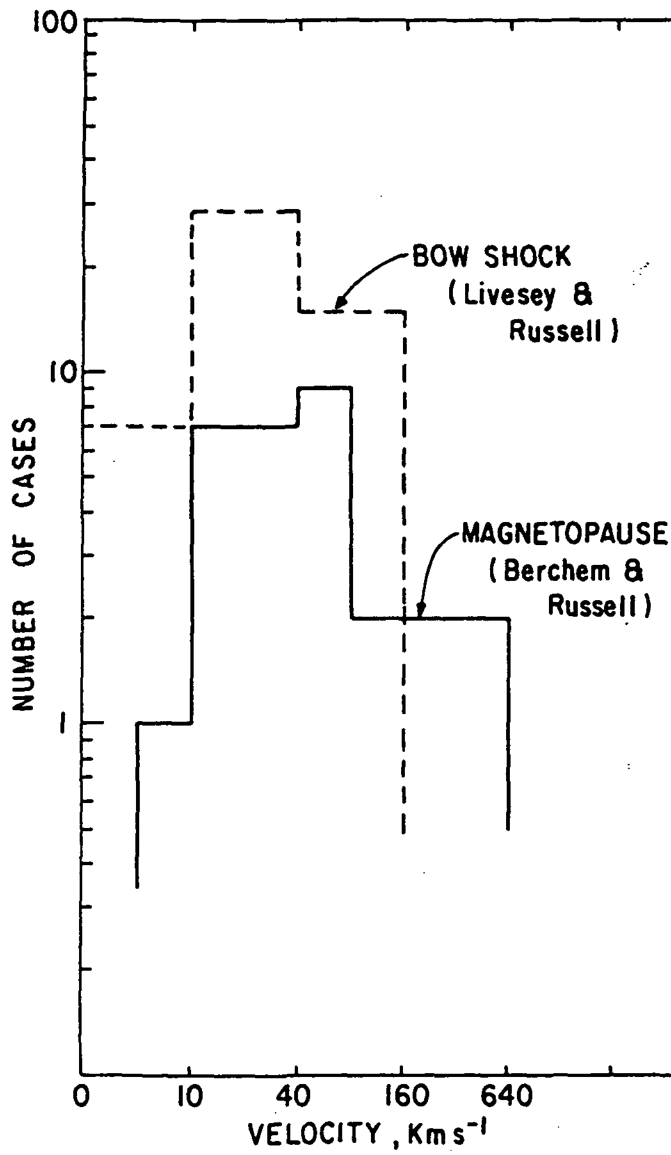
16. Abstract Cont'd.

of time resolution, and other development of the measurement techniques involved rather than from cooperative research involving more than one spacecraft. Thus much new material awaits discovery and exploitation.



TOTAL = 361
THEORY = 42
100
50
ISEE-1
PUBLICATIONS YR-1
20
ISEE-3
TOTAL = 231
THEORY = 21
10
5
DOES NOT INCLUDE
NEWS RELEASES, ETC
2
1
1977
1978
1979
1980
1981
1982
1983
CALENDER YEAR

Figure 1.



100
10
1
NUMBER OF CASES
BOW SHOCK
(Livesey & Russell)
MAGNETOPAUSE
(Berchem & Russell)
0
10
40
160
640
VELOCITY, Km s^{-1}

Figure 2.

Table 1.

THE MAJOR CONTRIBUTIONS BY ISEE-1 AND -2 TO THE KNOWLEDGE OF MAGNETOSPHERIC PLASMAS INCLUDE:

- MAPPING THE STRUCTURE OF THE EARTH'S FORESHOCK, AND BRINGING THE STUDY OF THE PHENOMENA THERE TO THE LEVEL OF FUNDAMENTAL PHYSICAL PROCESSES.
- DEMONSTRATING RECONNECTION, STEADY STATE AT THE MAGNETOPAUSE AND TRANSIENT AT FLUX TRANSFER EVENTS, AND ADVANCING THE STUDY OF THE MAGNETOPAUSE AS A ROTATIONAL DISCONTINUITY.
- ESTABLISHING THE IMPORTANCE OF BOUNDARY LAYERS, ESPECIALLY THE PLASMA SHEET BOUNDARY LAYER, FOR MAGNETOSPHERIC STRUCTURE.
- EXTENDING THE STUDY OF COMPOSITION IN THE MAGNETOSPHERE, ESPECIALLY WITH RESPECT TO PLASMA SOURCES.
- EXTENDING THE STUDY OF PLASMA WAVES IN THE MAGNETOSPHERE.
- RE-ESTABLISHING THE COLLISIONLESS SHOCK AS A TOPIC FOR ACTIVE RESEARCH.
- MAKING VALID ELECTRIC FIELD OBSERVATIONS AT ALL POINTS IN THE ORBIT.

successfully placed in the desired orbits. By this time it had been decided that ISEE-1 should form one of the principal contributory spacecraft to the IMS.

To illustrate the present state of the ISEE project Figure 1 shows a plot of the number of refereed publications per year, representing work derived from ISEE-1 and -2 observations, with those from ISEE-3 observations shown separately. One can see that the project has just reached its productive peak, so that many more studies remain to be completed, and among these may be major advances in magnetospheric physics.

The high degree of productivity illustrated in Figure 1 results from a number of features of the instruments forming the ISEE payload as well as from the Mother-Daughter configuration. At the time they were designed the ISEE instruments were very advanced in concept; the electric field instruments incorporated recent experience on other spacecraft and sounding rockets, the particle instruments had adequate time resolution and incorporated an appreciation of the essential three-dimensional nature of the phenomena to be encountered. The importance of ionic composition measurements was appreciated. The cosmic ray instruments were capable of isotopic resolution and plasma wave observations were possible at adequate sensitivity over the whole necessary frequency range.

After overcoming some early problems concerning the determination of the vector separation of the two spacecraft to the required accuracy, it became clear that, indeed, the Mother-Daughter concept allowed the breaking of the ambiguity inseparable from measurements made on moving boundaries by a single set of instruments which are themselves in motion. Figure 2 shows a histogram of measurements by Russell and Co-Workers on the distribution of velocities of the bow shock and of the magnetopause (Ref. 2). Very early results which indicated the promise of the project were published in a special issue of Space Science Reviews (1979).

In this paper I will try to give an idea of the advances in knowledge of the plasma physics of the magnetospheric system made by ISEE-1 (with essential help from ISEE-2). It is completely impossible to cover at reasonable length all the topics on which ISEE investigators have worked successfully. A selection of such topics, certainly including the most important, is given in Table 1.

Clearly, from such a rich assortment only a few examples can be chosen, and I will choose those with which I am familiar in my own scientific work and aim to discuss new results rather than to provide a comprehensive and critical review. Such a review is, in any case, better classified by subject matter.

2. OBSERVATIONS AT THE MAGNETOPAUSE

Observations by ISEE-1 at the magnetopause have contributed to studies of its motion and thickness, to studies of the boundary layer at low latitude, and, most importantly, to the search for unequivocal proof of merging between the interplanetary magnetic field and the terrestrial field. An elegant indirect method of sensing the position and motion of the magnetopause from the inside was developed by Williams and co-workers (Ref. 3); involves measuring the maximum energy that an initially trapped particle can have without being lost as a result of crossing the magnetopause during its gyro motion. This method has proved valuable in the study of magnetopause motions and stability. Much evidence suggests the magnetosphere to be open at times; nonetheless, it has proven remarkably difficult to observe the signatures that merging theory predicts should be present, and not everyone has yet been convinced that merging takes place and is an essential part of the functioning of the magnetospheric system.

Until ISEE, attempts to measure a component B_n of the magnetic field along the magnetopause normal provided potentially the most convincing evidence of merging, because of the high time resolution which can be obtained with magnetometers (Ref. 4). Although the evidence for $B_n \neq 0$ was reasonably convincing, attempts to detect plasma jetting by the plasma instrument on HEOS were unsuccessful (Ref. 5), leading to the idea of reconnection as a transient process confined to the cusp region.

The ISEE instrument complement permitted electric field and 3-D plasma measurements in the region of the magnetopause with time resolution of order 1 second, and this has provided compelling new evidence suggesting that merging takes place both as a localized steady state phenomenon and at flux transfer events. However, even the ISEE observations have not yet allowed the detailed study of the "diffusion" region, but merely the predicted consequences of merging taking place at a point remote from that of the observation.

Mozer et al. (Ref. 6) reported observations of tangential electric field components on both sides of the magnetopause and deduced a magnetopause thickness of 300 ± 150 km from the crossing time of 15 seconds; this underlines the remarks made above about the time resolution required for meaningful reconnection diagnosis. Examples of flow speeds ($\sim$ 450 km s^{-1}) in the boundary layer higher than in the magnetosheath were reported by Paschmann et al. (Ref. 7), using the fast plasma instruments on ISEE-1 and -2 which obtain three dimensional distribution functions in 9 seconds, repeated every twelve seconds. The plasma and magnetic field observations confirmed that the magnetopause was at these times a rotational discontinuity with an average normal field component of 5.4 nT, and moving at 10 km s^{-1}. However, crossings with high speed flows in the boundary layer were not easily found. As will be pointed out below, this may result from the short time available for magnetopause observations in a given orbit, and also from geometrical considerations. Furthermore, all of the observed cases of accelerated flow could not be analyzed; indeed no complete statistical study of ISEE magnetopause crossings has been made (Ref. 8). The eleven sets of measurements analyzed by Sonnerup et al. (Ref. 8) and Paschmann et al. (Ref. 9), provide simultaneous, direct, and quantitative evidence that $B_n \neq 0$; and energized particles either leaking across or reflected from the magnetopause are observed at on least a subset of crossings. Most, but not all, workers in the field regard this as persuasive evidence for dayside reconnection as a quasi-static phenomenon, even though it does not suggest the stable steady state process of Dungey (Ref. 10).

Aggson et al. (Ref. 11) have pointed out that both acceleration and deceleration across the magnetopause are consistent with a rotational discontinuity structure. Once this is pointed out, it becomes clear that certain regions of the magnetopause are geometrically favored for merging. This idea is being developed, (Ref. 12), (Ref. 13).

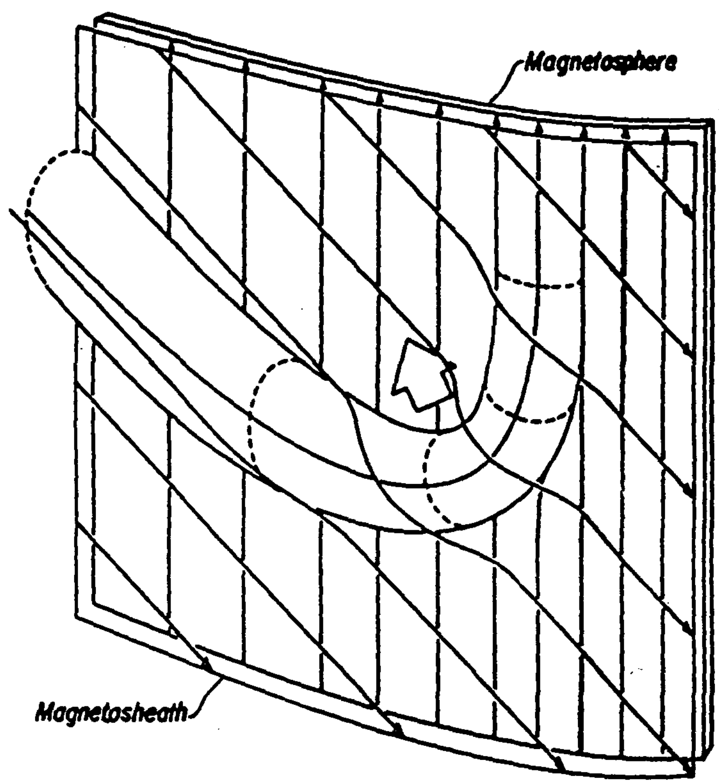
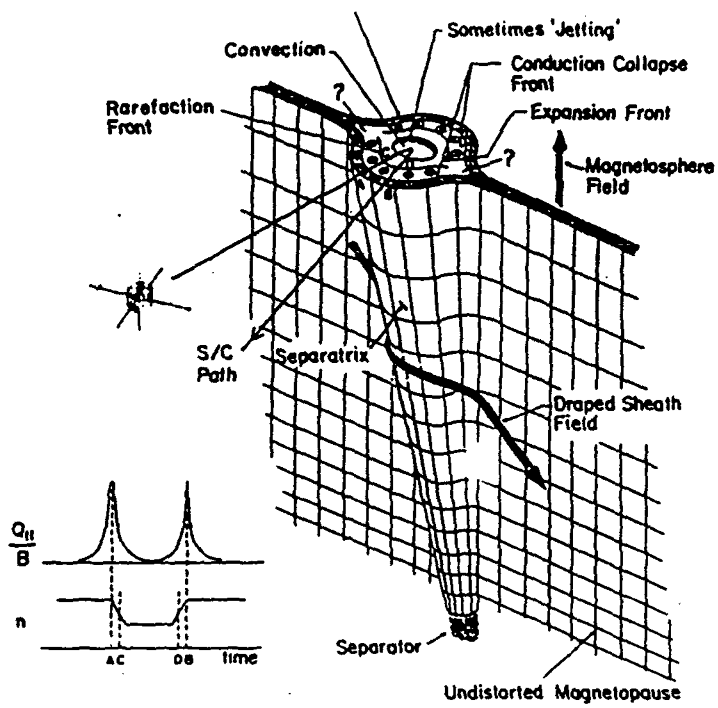


Figure 3.



Sometimes 'Jetting'
Convection
Conduction Collapse Front
Rarefaction Front
Expansion Front
Magnetosphere Field
S/C Path
Separatrix
Draped Sheath Field
n
time
Separator
Undistorted Magnetopause

Figure 4.

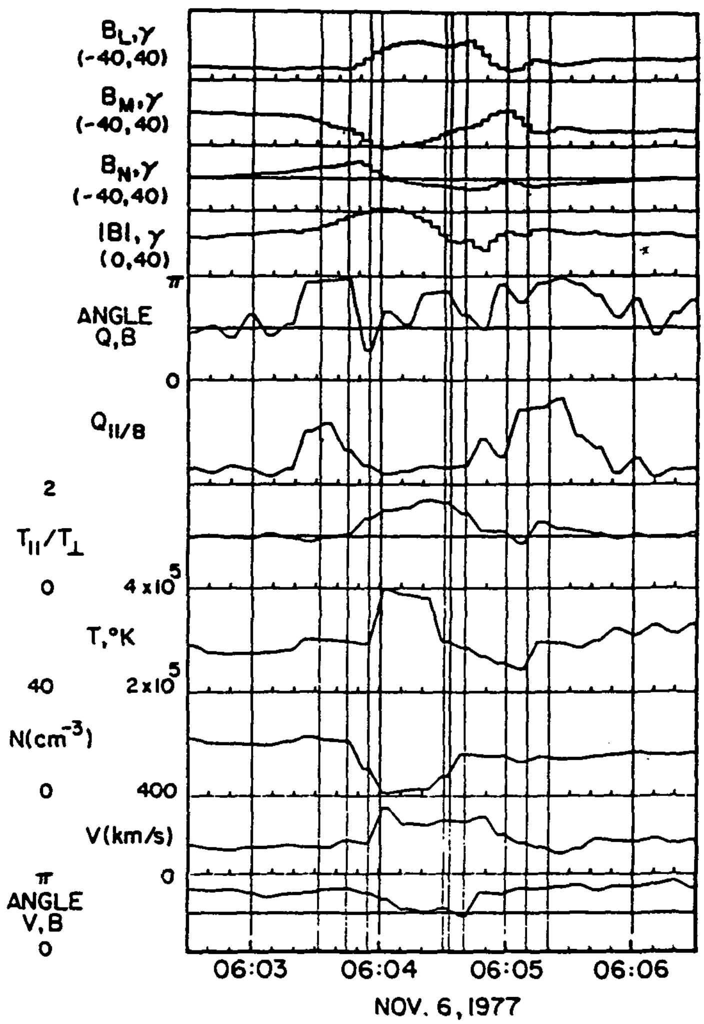

B_L, γ
(-40,40)
B_M, γ
(-40,40)
B_N, γ
(-40,40)
|B|, γ
(0,40)
π
ANGLE
Q,B
0
Q_∥/B
2
T_∥/T_⊥
0
4 x 10^5
T, °K
2 x 10^5
40
N(cm^-3)
0
400
V(km/s)
0
π
ANGLE
V,B
0
06:03
06:04
06:05
06:06
NOV. 6, 1977

Figure 5.

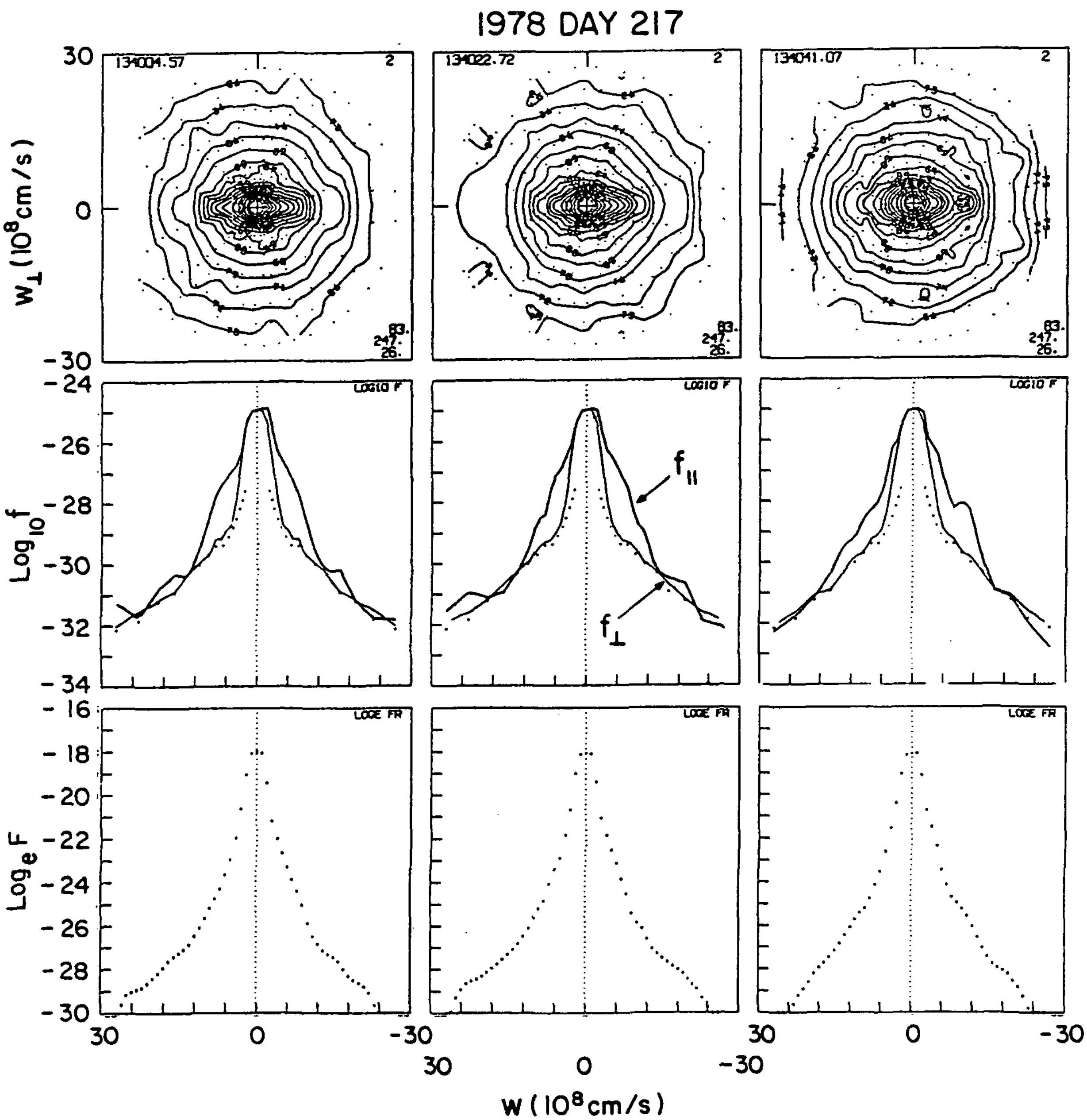
Another phenomenon involving merging is the so-called flux transfer event. As described by Russell and Elphic (Ref. 14) such an event, Figure 3, takes the form of a bulge moving across the magnetopause, which provides for a normal field component and suggests the connection of a magnetospheric flux tube to an interplanetary flux tube at a point remote from the observer.

The spacecraft moving at $\sim$ 2 km s^{-1}, is almost at rest in comparison with the magnetopause, so the observations are carried out along a trajectory largely determined by the magnetopause motion. Thus, in traversing a flux transfer event the spacecraft is carried through it along a path which can have varying topology, Figure 4.

It became clear that the ISEE-1 Vector Electron Spectrometer (VES) observations of flux transfer events displayed a theme with several variations. The best observed events showed a density excursion to a value between the sphere and sheath densities, an increase in electron temperature anisotropy above that in the sphere or sheath, and, between a pair of heat flux maxima, a flow velocity orthogonal to the local magnetic field, Figure 5. Variations were seen in the temperature profile, the bulk speed did not always increase, and heat flux peaks did not always occur. A model has been developed which explains the canonical signatures (Ref. 15); many of the variations can also be explained as resulting from the path followed by the spacecraft in space-time relative to the structure.

We associate the heat flow peaks commonly observed with the traversal of the separatrix of a merging event; the diffusion region being several earth radii from the site of observation. Heat flow continues while crossing magnetic field lines anchored in the highly conductive diffusion region; the signal of its switch on or off travels with the electron thermal speed, faster than the jetting plasma seen in the center of the flux transfer interval where it is associated with the straightening kink in the magnetic field, Figure 5. In this way the angular half widths of the reconnected tubes are estimated to be 20-40 degrees. The thickness of the heat flow layers imply scale lengths in the diffusion region of several ion Larmor radii. Examples of FTE's where reconnection has ceased show "B but not Q" signals, and "Q but not B" indicates a transient start up phase. Verification of these detailed predictions, together with the fact that the magnetic flux transfer rate implied by the recurrence rate of F.T. events can replenish between substorms the magnetic flux reduction in the magnetotail observed during a substorm, provide powerful arguments for the validity and importance of the reconnection hypothesis. Unlike the apparent situation in the quasi-steady reconnection phenomena reported by Paschmann and Sonnerup the shear layer cannot be described as standing in the magnetosheath flow, and its direction of propagation is not aligned with the local boundary normal direction. This model can explain the VES observations at 31 flux transfer events in the framework of the encounter of the spacecraft with the results of reconnection in a region remote from the region of observation.

Altogether, the ISEE measurements have provided very persuasive evidence that the magnetopause is often at least locally a rotational discontinuity across which plasma flows and can be accelerated or decelerated. If we add evidence obtained in the deep tail by ISEE-3, much of which can be consistently interpreted in the framework of formation of plasmoids by reconnection, we see



1978 DAY 217
134004.57
134022.72
134041.07
$W_\perp$ (10^8cm/s)
$Log_{10}f$
$f_{\parallel}$
$f_\perp$
LOG10 F
Log_eF
LOGE FR
W (10^8cm/s)

Figure 6.

that the concept of reconnection has become essential to describe the functioning of the magnetosphere. Quasi-steady state reconnection as envisaged by Paschmann et al. and episodic Flux Transfer Events are both of major importance.

3. BOUNDARY LAYER OBSERVATIONS

One part of magnetospheric studies to which ISEE-1 has contributed is the study of the structure and plasma population of the Low Latitude Boundary Layer (LLBL).

The LLBL is the name given to a layer of plasma, within and bounded by the magnetopause, intermediate in density between the magnetosheath and the outer magnetosphere, which is often present at low latitudes in the sunward direction. Plasma observations, taken in the LLBL by the ISEE-1 and -2 plasma instruments, have been discussed by Sckopke et al. (Ref. 16). They conclude that the plasma in the boundary layer is a mixture of magnetosheath and magnetospheric components, confirming, for example, previous mass spectrometer observations made by Peterson et al. (Ref. 17), also using ISEE-1, and providing further evidence of an open magnetosphere.

Sharp et al. (Ref. 18) made an analysis of electron beams with a broad energy spectrum peaking at $\sim$ 160 eV frequently observed streaming in both directions along the magnetic field at altitudes of $\sim$ 1 R_E above the auroral zone. They suggested that these electrons were accelerated from the ambient plasma, where they are produced as secondary electrons at eV energies. Recently Collin et al. (Ref. 19), have studied field aligned beams of energy $\sim$ 100 eV, streaming in both upward and downward directions at 3000-8000 km in auroral latitudes, with typical fluxes $\sim 3 \times 10^9$ (cm,sr,s,keV)$^{-1}$, and half angles of $\lesssim 10°$ in width were measured. Klumpar and Heikkila (Ref. 20) have also frequently observed similar fluxes of electrons streaming in beams at 10 to 100 eV energy from the ionosphere in the auroral latitudes. Finally, Burch et al. (Ref. 21) report streaming electrons on the equatorward side of the polar cusp, observed with the high altitude DE spacecraft, which they identify as carriers of the downward Birkeland currents.

It therefore appears well established that field aligned electron beams may be observed a large fraction of the time at auroral and cusp latitudes and altitudes of a few hundred km to $\sim$ 1 R_E. The origin of these beams is the ionosphere, and they appear on field lines which also pass through the region occupied by the LLBL. Ogilvie, Fitzenreiter and Scudder (Ref. 22) have shown that electron beams with similar properties to those observed at lower altitudes are observed a large fraction of the time in the LLBL. The energy, energy spread, and flux density of these beams are the same in the LLBL as at lower altitudes, and the collimation observed in each region is in accordance with conservation of the first adiabatic invariant. In Figure 6 we show an example of bidirectional electron streamming in the LLBL. In the upper part of the figure we show contour plots of the distribution function obtained by the VES on ISEE-1, transformed to the electron rest frame and plotted against $W_\parallel$ and $W_\perp$. Below we see the corresponding reduced distribution function,

$$F(w_\parallel) = 2\pi \int_0^\infty f(w_\perp, w_\parallel)\, w_\perp\, dw_\perp \tag{1}$$

and cuts across the distribution function, $f(V_{\parallel})$, $f(V_{\perp})$.

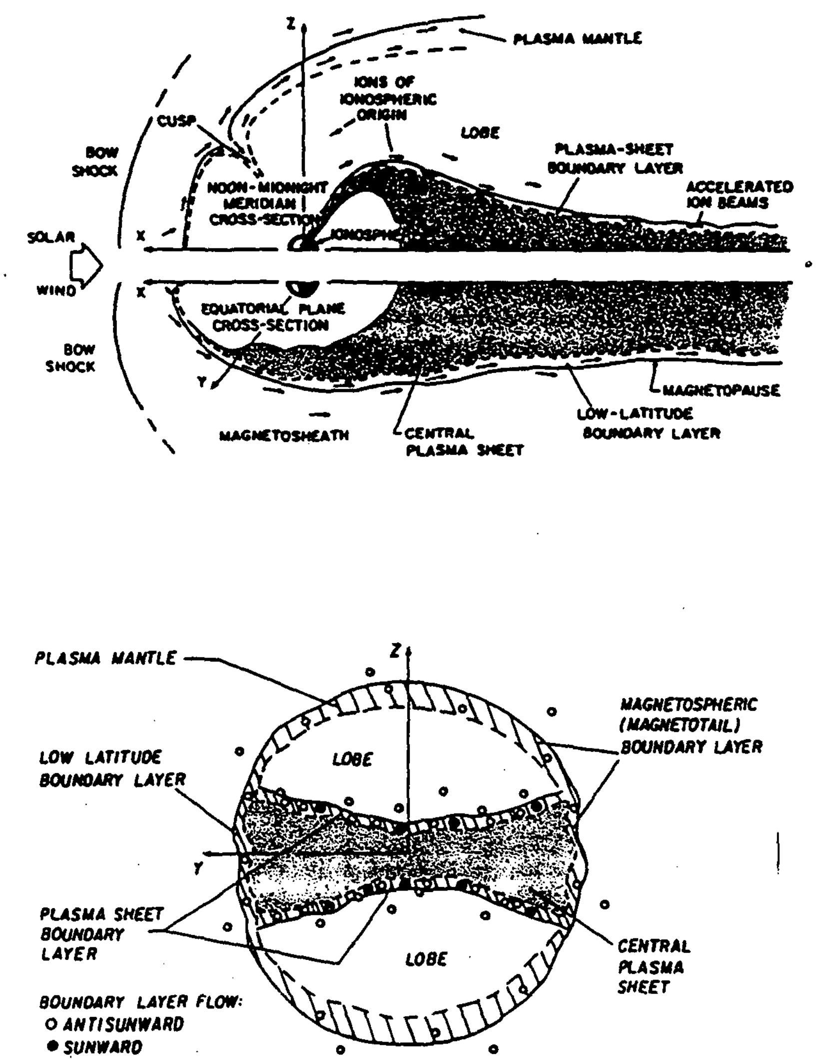
The distribution function of electrons in the LLBL shows the plasma to resemble a mixture of components from the magnetosheath and the outer magnetosphere, as found by Sckopke et al. (Ref. 16). To these expected components must now be added field aligned beams of electrons, in the energy range 20-200 eV, which occur rather frequently.

We tentatively identify these field aligned electrons with the electrons observed at altitudes between a few hundred km and 15000 km at auroral latitudes by previous workers. The electrons are collimated on magnetic field lines when close to the magnetopause as a result of conservation of the first adiabatic invariant. They can be observed in the LLBL when their phase density becomes comparable to that of the magnetosheath component of the electron population, that is, when the magnetosheath density and temperature are favorable and the position of observation is not connected to an open part of the magnetosphere. A search to find time coincident observations of electron beams of similar intensity at low altitudes and in the LLBL, has been made, but has not yet been successful.

While the high latitude boundary of the plasma sheet was previously known as the seat of particle beams, currents, and waves, recent ISEE-1 observations have greatly expanded knowledge of this region at least in the near magnetotail. Here again the emphasis, which became possible with ISEE, on basing the interpretation on the particle distribution function rather than simply on moments of that distribution has proven important.

In the plasma sheet boundary layer, which seems to be a permanent and important component of the magnetotail, counterstreaming electron and multi-species ion beams are frequently observed, DeCoster and Frank (Ref. 23); Lui et al. (Ref. 24), in contrast to the sparsely populated lobes and the hot, approximately isotropic population of the plasma sheet. The source of the ions moving away from the sun is the ionosphere, although the mechanism of their acceleration is not understood. The source of the sunward flowing ion beams is not yet understood, although using velocity dispersion Williams (Ref. 25) puts it at $\sim$ 100 R_e down the magnetotail, and interpretation of ISEE-3 observations made beyond 60 R_e in the tail will undoubtedly prove useful. It is generally believed, supported by observation of electrostatic noise in the boundary layer, that the plasma sheet population owes its large thermal energy to interaction with these ion beams. Focusing attention on the boundary layers of the magnetosphere is an important achievement of the ISEE spacecraft, because it has implications for the theory of the magnetotail.

A study of the plasma sheet boundary layer over the full energy range of ions and electrons observed by ISEE, and also including magnetic and electric fields and waves, has recently been conducted by Parks et al. (Ref. 26). This research group was made up of eight organizations from four countries all associated with the ISEE spacecraft. The first conclusion from several hundred observations is that the boundary layer of the plasma sheet normally exists distinct from the lobe and the plasma sheet itself. Ions and electrons over a wide energy range were observed flowing in both directions along the magnetic field there and the low energy (< 2 keV) electrons showed reduced



PLASMA MANTLE
IONS OF IONOSPHERIC ORIGIN
LOBE
CUSP
BOW SHOCK
NOON-MIDNIGHT MERIDIAN CROSS-SECTION
PLASMA-SHEET BOUNDARY LAYER
ACCELERATED ION BEAMS
SOLAR WIND
X
Z
EQUATORIAL PLANE CROSS-SECTION
BOW SHOCK
Y
MAGNETOSHEATH
CENTRAL PLASMA SHEET
LOW-LATITUDE BOUNDARY LAYER
MAGNETOPAUSE
PLASMA MANTLE
MAGNETOSPHERIC (MAGNETOTAIL) BOUNDARY LAYER
LOW LATITUDE BOUNDARY LAYER
LOBE
PLASMA SHEET BOUNDARY LAYER
CENTRAL PLASMA SHEET
BOUNDARY LAYER FLOW:
O ANTISUNWARD
● SUNWARD

Figure 7.

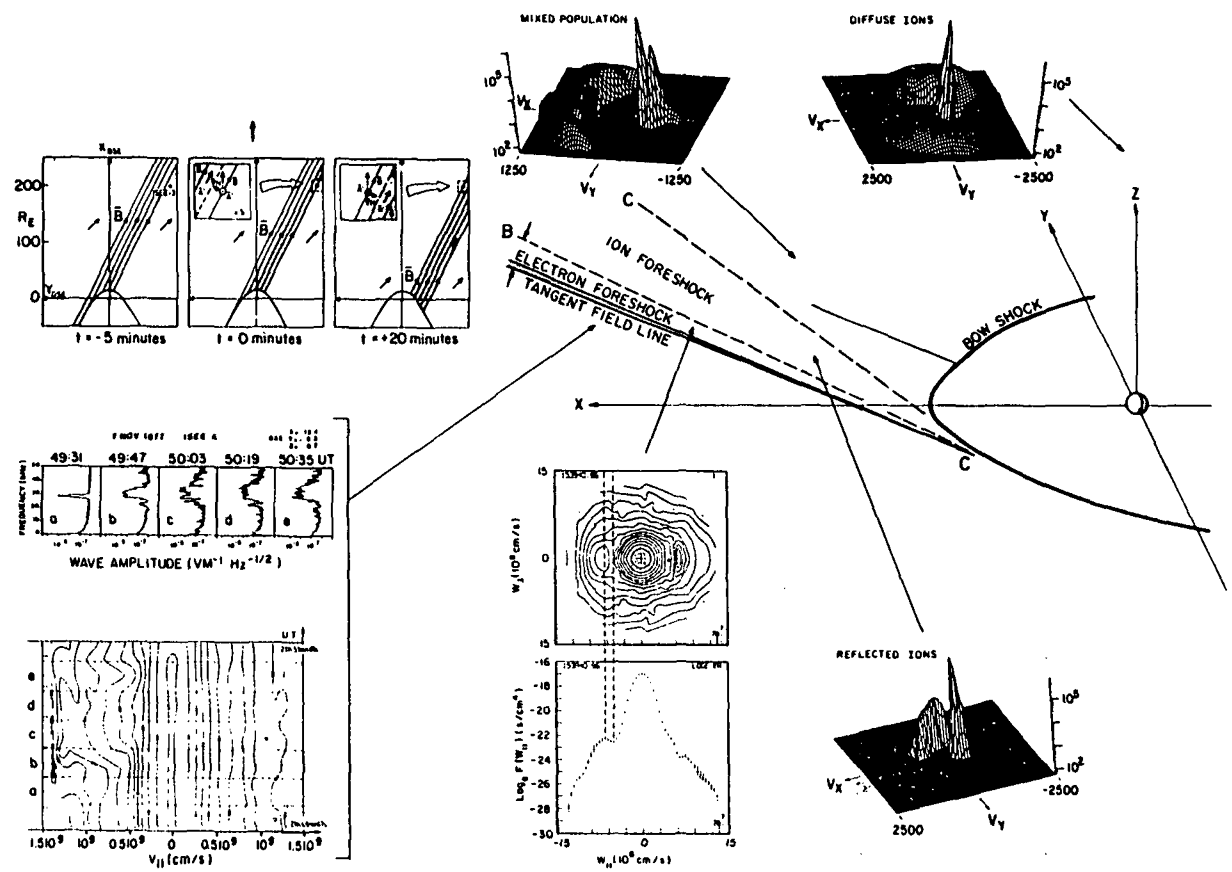

MIXED POPULATION
DIFFUSE IONS
REFLECTED IONS
BOW SHOCK
ION FORESHOCK
ELECTRON FORESHOCK
TANGENT FIELD LINE
t = -5 minutes
t = 0 minutes
t = +20 minutes
49:31
49:47
50:03
50:19
50:35 UT
WAVE AMPLITUDE (VM⁻¹ Hz⁻¹/²)

Figure 8.

distribution functions unstable to electrostatic instabilities. Broad band electrostatic wave activity was observed, with significant enhancement below the plasma frequency. Eastman et al. (Ref. 27), interpreting hot plasma observations with the aid of those of the mass spectrometer, provide a similar picture of the plasma sheet boundary layer. Figure 7, adapted from Eastman et al. (Ref. 27), illustrates the present view of these layers.

4. OBSERVATIONS IN THE FORESHOCK; PARTICLES

Although it is not strictly correct to say that the foreshock region of the interaction of the solar wind with the earth was discovered with the ISEE spacecraft, its true nature and importance were not realized or made apparent until the ISEE data set became available. Results of the initial ISEE-associated studies are described in a 231 page issue of the *J. Geophys. Res.*, (*86*, 4319, 1981), so that only a summary, following that given by Tsurutani and Rodriguez (Ref. 28) will be attempted here, together with an account of some important subsequent work on the electron foreshock by Fitzenreiter, Klimas, and Scudder (Ref. 29), using the ISEE VES. Figure 8, which is a composite of figures from various sources (Tsurutani and Rodriguez, Paschmann, Eastman, Sanderson, Hoppe, Fitzenreiter and Klimas) shows the nature and locations of the ISEE discoveries in the foreshock region. Starting with the ion distribution functions, the three perspective contour plots show how, close to the ion foreshock C–C, the distribution function has a component of reflected ions, with velocities $\sim$ 3 times that of the solar wind, moving upstream. Indeed, the diagram in the top left-hand corner of Figure 8 shows how ions of MeV energy are observed at ISEE-3, situated 200 R_e upstream, when the magnetic field is aligned in the correct direction. Rotation of the field in azimuth can carry the reflected beam of ions across the position of the spacecraft as indicated. Further away from the ion foreshock a "mixed" population of reflected ions is measured, and, as they are convected downstream the distribution function of these ions relaxes to a ring-like form, as shown at the top right of Figure 8. In the electron foreshock, the highest energy electrons form a beam closest to the tangent field line. Observations up to 16 keV have been made in the electron foreshock by Anderson et al. (Ref. 30). Low energy electrons are positioned further from the tangent line as a result of velocity dispersion introduced by the solar wind. In the lower part of the figure we see a contour plot of a typical electron distribution function, and below it a plot of $F_\parallel$, the reduced electron distribution function, showing the beam. In the lower left, we see how a momentary shift in the azimuth of the magnetic field can cause the spapcecraft to cross the tangent line (at a) and penetrate more deeply into the electron foreshock (b,c and d), and then retreat towards the tangent line (at e). The upper part of the lower left panel is a plot of wave amplitude ($VM^{-1}\,H_z^{-1/2}$) versus frequency, and one sees that the width of the plasma line increases with depth of penetration. The lower part of this panel is a contour plot of the reduced distribution function $F(V_\parallel)$ against time.

Now that the structure of the foreshock is largely understood, work is concentrated on gaining an understanding of the many features of the distribution functions of particles and waves, and their interaction in this complex region. The ISEE instrument complement is the first which has adequate time resolution and velocity space coverage for this task. The discussion of the plasma and MHD wave population in the foreshock will be taken up again below.

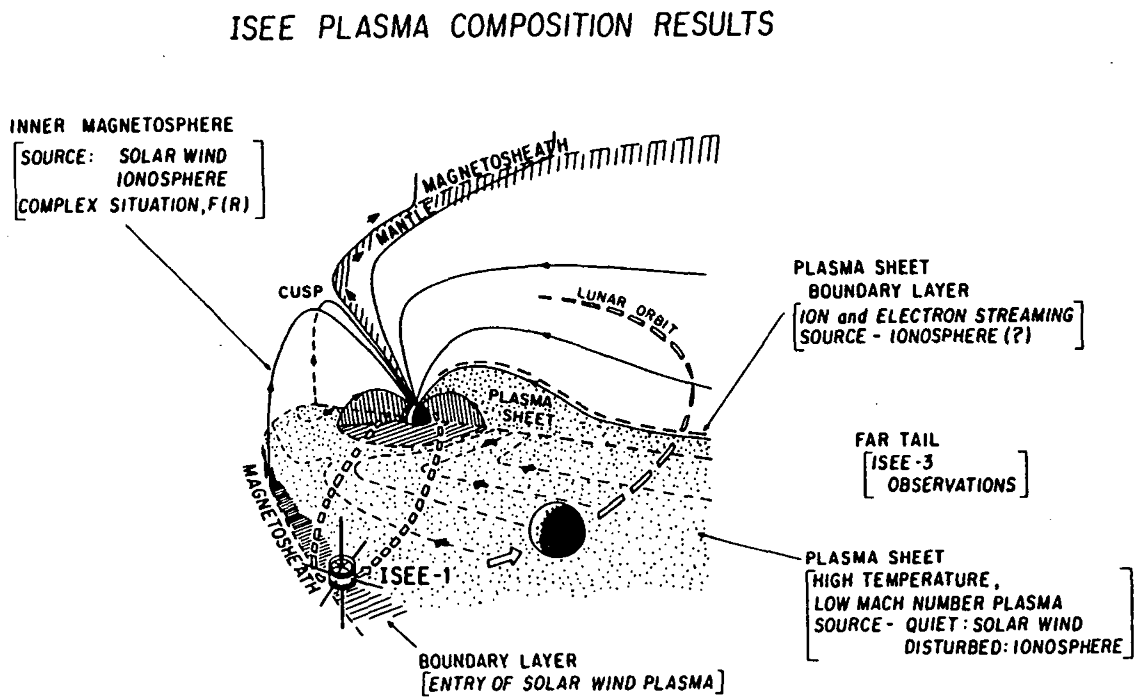

ISEE PLASMA COMPOSITION RESULTS
INNER MAGNETOSPHERE
[SOURCE: SOLAR WIND
IONOSPHERE
COMPLEX SITUATION, F(R)]
MAGNETOSHEATH
MANTLE
CUSP
LUNAR ORBIT
PLASMA SHEET
MAGNETOSHEATH
ISEE-1
PLASMA SHEET
BOUNDARY LAYER
[ION and ELECTRON STREAMING
SOURCE - IONOSPHERE (?)]
FAR TAIL
[ISEE-3
OBSERVATIONS]
PLASMA SHEET
[HIGH TEMPERATURE,
LOW MACH NUMBER PLASMA
SOURCE - QUIET: SOLAR WIND
DISTURBED: IONOSPHERE]
BOUNDARY LAYER
[ENTRY OF SOLAR WIND PLASMA]

Figure 9.

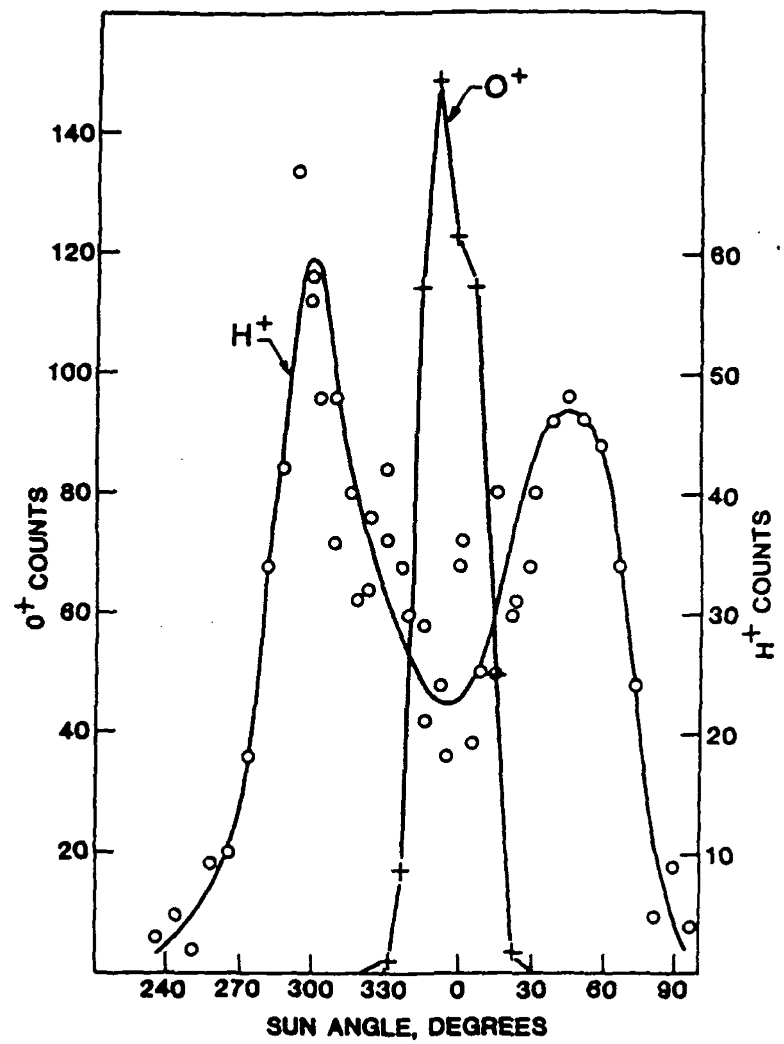
5. MAGNETOSPHERIC PLASMA COMPOSITION

This account draws heavily upon the review of Sharp et al. (Ref. 31) and on papers by Parks et al. (Ref. 26), Eastman et al. (Ref. 27), and Orsini et al. (Ref. 32). Figure 9 attempts to indicate those topics on which ISEE-1 has provided an increase in our knowledge of plasma composition in the magnetosphere. Data were mainly provided by the energetic ion mass spectrometer, which was more sensitive than previous instruments measuring plasma composition had been, and was thus able to make useful observations almost everywhere in the magnetosphere and near tail out to a distance of 23 R_E. Parenthetically, care must be taken in reading accounts of these measurements; both the region around 23 R_E and the region beyond 60 R_E subsequently studied with ISEE-3 are customarily referred to as the "distant" magnetotail.

In the course of measuring the entry of solar wind plasma to the magnetotail via the boundary layers, work has been done on comparing the relative contributions of the solar wind and the ionosphere as plasma sources for the magnetosphere as a whole, and particularly for the magnetotail. By assuming that He^{++} is of solar wind, and O^+ of ionospheric, origin, Peterson et al. (Ref. 33) have shown that the plasma sheet is almost entirely composed of plasma from the solar wind during quiet intervals, but has an important ionospheric component during active times.

Previous observations (e.g., Hones et al. Ref. 34) have shown that the dominant ion population of the plasma sheet has a temperature in the keV range, with a drift speed less than the thermal speed. Streaming ions and electrons are observed mostly in the boundary layer of the plasma sheet, first clearly identified as a separate structure by the ISEE instruments. These beams which are observed streaming towards and away from the earth have densities in the 10^{-2} cm^{-3} range, have directed velocities of hundreds of km s^{-1} and Mach numbers large compared to 1. Both O^+ and H^+ beams occur and those streaming away from the earth are believed to be of ionospheric origin; the acceleration mechanism is at present not understood, although the angular distributions, Figure 10, may provide a test of theoretical suggestions. The plasma sheet is populated both by the inward convection of material from the magnetotail boundary layers and by the thermalization of such beams. The importance of the plasma sheet boundary layer and the characteristics and composition of the beams found there are new results of ISEE investigations; the exploratory observations beyond 60 R_e by ISEE-3, not discussed here, are also of fundamental importance to our understanding the magnetotail.

In the inner magnetosphere, an important contribution of the ISEE composition instrument has been the measurements of the radial dependencies of plasma composition near the equatorial plane. Figure 9 indicates that, again, both the solar wind and the ionosphere are important contributors up to an energy per charge of 17 keV/Q, and that their relative importance varies with magnetic activity. ISEE results show that ions are injected into the ring current at quiet times, and around L = 6, that the solar wind may be a more important source relative to the ionosphere during storms than it is during quiet times, but these results have not been decisive for an understanding of the sources and decay mechanisms of the ring current. The composition, dynamics, and the decay mechanism of the ring current remain, therefore, important subjects of research.



O+
H+
140
120
100
80
60
40
20
60
50
40
30
20
10
0+ COUNTS
H+ COUNTS
240
270
300
330
0
30
60
90
SUN ANGLE, DEGREES

Figure 10.

In addition to this work in the magnetosphere and the magnetotail, Peterson et al. (Ref. 35) have studied the effect of the thermalization of minor ions behind the bow shock, leading to halo type velocity distributions in the magnetosheath, and have also located He^+ and O^+ ions in the boundary layer. These ions were presumably accelerated along field lines from the ionosphere to an energy several keV where their gyro radius in the LLBL exceeds the thickness of the magnetopause, and they can then be lost to the magnetosphere.

6. PLASMA WAVE RESEARCH WITH ISEE

ISEE-1 carries a spectrum analyzer, a swept frequency receiver, a wave normal analyzer, and a wide band receiver; ISEE-2 carries a simpler spectrum analyzer and a wide band receiver. This extensive instrumentation has made observations which are a considerable advance upon previous plasma wave observations in the solar wind, the magnetosheath and in the magnetosphere (Ref. 36). There is also an active sounder-receiver instrument acting between the ISEE-1 and ISEE-2 spacecraft (Ref. 37). ISEE-3 also carries a plasma wave instrument, the results from which, though very important, fall outside the scope of this paper.

An important reason for the success of ISEE in plasma wave studies has been that the particle instrumentation has the capability to exhibit distribution functions which can be used to identify instabilities and wave modes and make quantitative predictions. Early results were discussed by Gurnett et al. (Ref. 36), and we will make a selection of some of the results published since that time.

We note that the exciting encounters of the Voyager spacecraft with Jupiter and Saturn captured the interest of the community—especially in the plasma wave subdiscipline--towards comparative magnetospheric studies. The rapid rotation rate and unaligned dipole of Jupiter make a single encounter there equivalent to a much longer period of study with a spacecraft in an orbit such as that of ISEE. Some of the work done on plasma waves in the Jovian and Saturnian magnetospheres and the studies by Voyager of planetary decametric radiation will stimulate additional studies at earth; the ISEE data set contains material for a number of years of such efforts.

Figure 11, adapted from Shawhan (Ref. 38), illustrates some work already completed using the ISEE data set. Particles traveling along the magnetic field upstream from the bow shock excite a variety of wave modes, as described above in the section on the foreshock. Russell and Hoppe (Ref. 39) have discussed these effects, which have been seen at Mercury, Venus and Jupiter as well as at the Earth, where the ISEE-1 and -2 spacecraft have made many good measurements. Observation of particles and waves associated with interplanetary shocks implies that the generation of upstream particles, which provide the free energy for wave generation, is common to all collisionless shocks. Despite the large amount of observational material provided by ISEE and other spacecraft, this is still a very active area of research, and the way in which the various phenomena fit together is not yet understood. Both the distribution function and the field-shock normal orientation affect the growth of waves and the consequent modification of the particle characteristics in a highly non-linear interaction. Such facts as are available include:

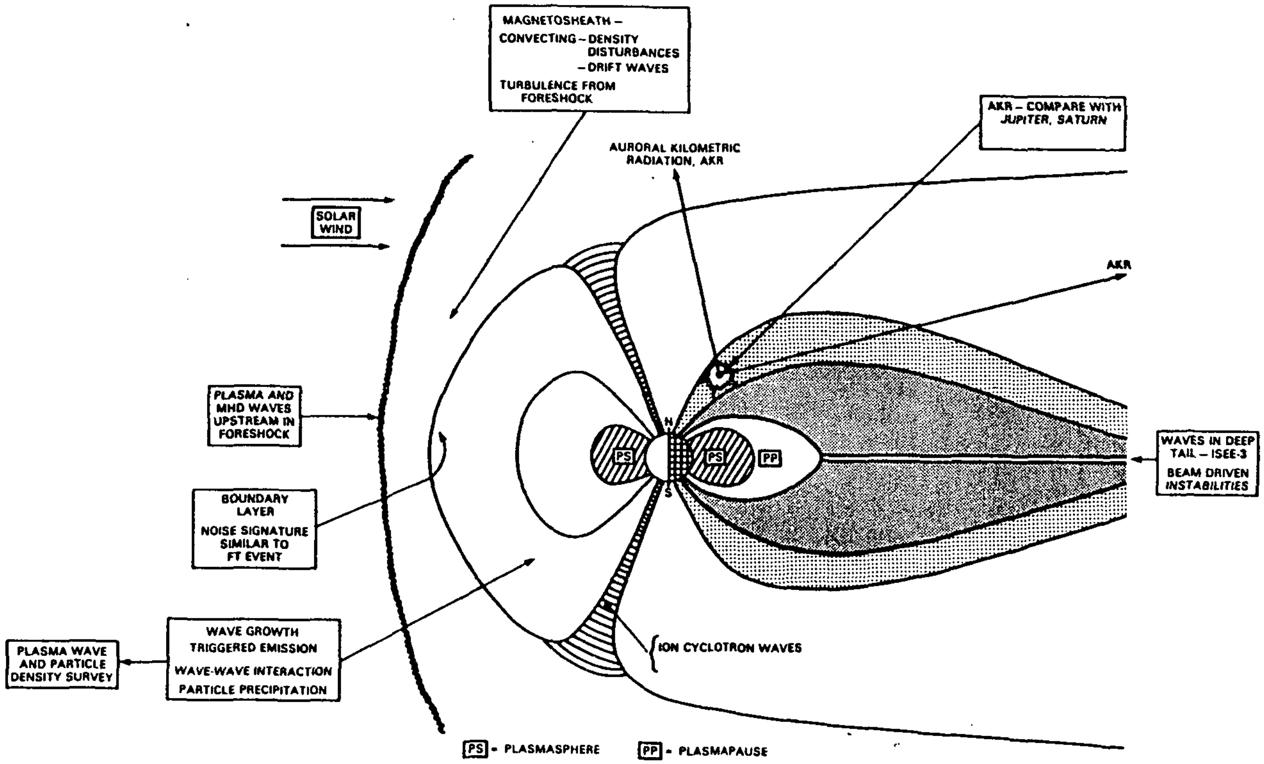

MAGNETOSHEATH –
CONVECTING – DENSITY DISTURBANCES
– DRIFT WAVES
TURBULENCE FROM FORESHOCK
AKR – COMPARE WITH JUPITER, SATURN
AURORAL KILOMETRIC RADIATION, AKR
SOLAR WIND
AKR
PLASMA AND MHD WAVES UPSTREAM IN FORESHOCK
N
PS
PS
PP
S
WAVES IN DEEP TAIL – ISEE-3
BEAM DRIVEN INSTABILITIES
BOUNDARY LAYER
NOISE SIGNATURE SIMILAR TO FT EVENT
WAVE GROWTH
TRIGGERED EMISSION
WAVE-WAVE INTERACTION
PARTICLE PRECIPITATION
PLASMA WAVE AND PARTICLE DENSITY SURVEY
ION CYCLOTRON WAVES
PS = PLASMASPHERE
PP = PLASMAPAUSE

Figure 11.

1). The presence of ion and electron beams as described above and the importance of velocity dispersion in producing the observed velocity field.
2). Particle generated electrostatic waves at and below the local plasma frequency, most intensely near the tangent line.
3). Whistler mode waves with $f \sim 1$ Hz and low amplitude in the electron foreshock.
4). The well-known low frequency large amplitude electromagnetic waves associated with the ion foreshock, both in monochromatic ($f \sim 0.05$ Hz) form, and as steepened "shocklets".
5). Ions appearing at energies above those we are considering here.

Since the low frequency waves are blown back into the shock by the solar wind, their presence probably modifies the structure of the bow shock, which is quasi-parallel in this region.

In the magnetosheath, measurements by IMP 6 had already established that part of the turbulence observed there had been convected through the shock from the foreshock region, and that part was related to the relaxation of the distribution function of ions after they had passed through the shock (Ref. 40). ISEE studies have shown (Ref. 41) that, near the magnetopause, the spectrum of plasma waves in the magnetosheath includes non-oscillatory drifting mirror waves, which provide ducts for the ion cyclotron waves forming "lion roars", (Ref. 42) and also convecting density disturbances. This study also showed the similarity of the wave signatures of the low latitude boundary layer to those of flux transfer events.

Using various ground-based transmitters, a VLF receiver on ISEE-1, and observations at conjugate high latitude ground stations, a great deal of work has been carried out on wave-particle interactions in the outer magnetosphere, as a continuation of previous research using IMP 6 and other spacecraft. Wave amplification, the precipitation of electrons, triggered emissions, and wave-wave effects such as the production of sidebands have all been observed. The wave amplitude in the interaction region has been shown to be much larger than was thought (Ref. 43).

Auroral Kilometric Radiation is of special interest because its mechanism is not understood, and because it is the close analog to the decametric radiation of Jupiter and radio emission by other planets. Cross correlation between ISEE-1 and -2 provides information on the source position and motion, indicating the source has a low velocity, ~ 10 km^{-1}. ISEE instruments showed for the first time that AKR has considerable spectral fine structure, observable by means of frequency conversion (Ref. 44).

Calvert (Ref. 45) has observed ducting of AKR emissions in the earth's magnetosphere; suggests that field-aligned density depletions act as ducts for auroral kilometric radiation, which enters them on the equatorial side of the AKR source, Figure 12. Similarly, observations by ISEE of narrow band electromagnetic radiation appear to be an analog of the narrowband kilometric radiation from Jupiter and Saturn. Electrostatic emissions near the upper hybrid resonance frequency are suggested as the fundamental cause of both.

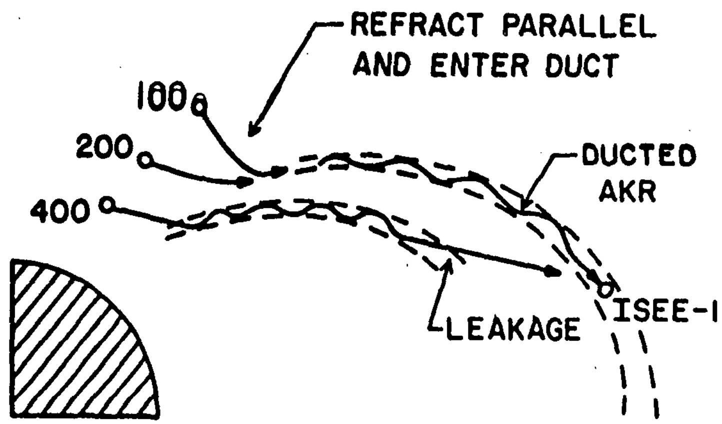

REFRACT PARALLEL
AND ENTER DUCT
100
200
400
DUCTED
AKR
LEAKAGE
ISEE-1

Figure 12.

7. D. C. ELECTRIC FIELD MEASUREMENTS

The measurement of D. C. electric fields is a comparatively new subdiscipline, and interpretation of the observations is still subject to disagreement; however progress has been made. Before ISEE Mozer et al. (Ref. 46) observed electrostatic shocks at altitudes from 1000 km to 8000 km. However, the electric field as well as particle data suggested that the auroral particle acceleration region must extend to higher altitudes than those reached by S3-3 (Ref. 47). The electric field observations on ISEE-1 provided the data needed to investigate this question. Mozer (Ref. 48) observed with ISEE-1 large electric fields at geocentric distances less than 7 R_E, which he interpreted as signatures of electrostatic shocks. Based on his electric field measurements on S3-3 and ISEE-1, Mozer (Ref. 48) concluded that the parallel electric field and auroral particle acceleration region might be confined to geocentric distances of a few earth radii and that the electric fields at higher altitudes would correspond to those from lower altitudes mapped up the magnetic field lines.

In contrast Aggson et al. (Ref. 49) interpreted some of the large electric fields observed on ISEE-1 as being transient inductive electric fields from the magnetotail collapse resulting from a sudden release of magnetic tension on auroral L shells at the time of substorm onset. Aggson's earlier observations on IMP 6 (Ref. 50) and more recent measurements on GEOS-2 (Ref. 51) support this interpretation.

8. CONCLUSION

It is clear from even such a condensed account as we have provided here that the work of the ISEE investigators, both during the IMS and at other times, has resulted in a high yield of new physical insight into the structure and mechanism of the magnetosphere, and its interaction with the solar wind, as well as other phenomena outside the scope of this review.

Table 1 is intended to summarize these topics. It does not include contributions, due principally to ISEE-3 investigators, to the study of the far magnetotail, even though such work will eventually add greatly to our knowledge of the behavior of the magnetosphere as a whole.

Because of the relatively advanced instrumentation, and because most of the important quantities were observed, the ISEE era is an example of the transition from exploratory observations to experimental measurements. However, although ISEE has probably been even more successful than was expected at its inception, a number of disadvantages have shown up. These should be pointed out, as they form lessons for the future, in which other international collaborative spacecraft programs will hopefully occur.

The first concerns the difficulty of collaboration with overseas experimenters without direct connections via some kind of computer network. The minimum requirement is however quite small, and as the cost of communications is likely to drop, this problem may be solved in response to non-scientific requirements before the next major project occurs.

The SWT has tended to meet at GSFC, or at least in the U. S., too frequently. This has been the result of difficulties with travel funds. It is vital that the international character of such a program be preserved without always requiring the non-U. S. members to do the traveling.

The ISEE project suggested and considered the idea of a central data system, but retreated to tape distribution for reasons of cost. The "data pool" tape was introduced to partially offset the problem of access to the relevant data of other experimenters. The idea was that the pool tape would form a handy index to data at low time resolution, and, if interesting things were seen in another data set, the corresponding PI could be contacted. The introduction of the laser disc allows all the observations to be regarded as a single data set, solving both this problem and that of archival storage. The latter has given some trouble to the ISEE project due to the deterioration of the original data tapes in storage.

Future spacecraft, to be compatible with the TDRSS system, will probably be operated in a "store and dump" mode. While this has advantages, the provision of a limited real time capability on ISEE-3 proved to be surprisingly easy as a post facto modification, and has useful applications.

The project has attempted to maintain a bibliography of ISEE-based refereed journal publications. It is certain that this does not contain all the entries it should, but an abstract of some of the more important review articles is given below. In many cases the selection was arbitrary, and the author apologizes to anyone who feels that his work is underrepresented. The author expresses his thanks to Drs. Anderson, Frank, Gosling, Parks, Russell, Sharp, Sugiura and Williams for useful comments during the preparation of this material, but they are not responsible for the views, and mistakes, made in this text.

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11. FIGURE CAPTIONS

Figure 1. Productivity of ISEE-1 and -2, and of ISEE-3, illustrated by the number of refereed scientific papers per year between 1977 and 1983.

Figure 2. Histograms of bow shock and magnetopause velocities by Livesey and Russell (Livesey, private communication, 1984, and by Berchem and Russell, 1982.

Figure 3. Qualitative sketch of a flux transfer event. Magnetosheath field lines, slanted arrows, have connected with magnetospheric field lines, vertical arrows, possibly off the lower edge of the figure. As the connected flux tube is carried by the magnetosheath flow in the direction of the large arrow, the stressed field condition at the "bend" tends to relax, effectively shortening the flux tube and straightening the bend. Magnetosheath field lines not connected to the magnetosphere drape over the connected flux tube and are swept up by its motion relative to the magnetosheath flow. (From Russell and Elphic, 1979).

Figure 4. In the model of Scudder and Ogilvie, 1984, motion of the magnetopause causes the stationary spacecraft to traverse a path across the separatrix and through the exit channel of a distant reconnection event. The signature of the event depends upon this path, and upon whether merging has just ceased or still continues.

Figure 5. Plasma signature of a flux transfer event. The upper three traces are of the magnetic field in γ, then the normalized heat flux, temperature anisotropy, and temperature, density, velocity, and angle between V and B. In this example the heat flux peaks framing the flux transfer interval and the "sling shot" velocity configuration are clearly seen.

Figure 6. This figure illustrates bi-directional electron streaming in the LLBL. Top, contours of the distribution function f_e; center, parallel and perpendicular cuts across f_e; bottom, plots of the reduced distribution F_e.

Figure 7. This figure shows the present view of the importance of bounday layers (after Eastman, 1982). The upper view shows cuts perpendicular to and in the ecliptic plane, the lower view is a cross section of the magnetotail.

Figure 8. A composite figure, discussed in the text, illustrating information obtained by ISEE about phenomena in the Earth's foreshock.

Figure 9. This figure illustrates observations of magnetospheric plasma composition obtained by ISEE-1 and -2.

Figure 10. Angular distributions of 628 eV O^+ and 212 eV H^+ ions measured in a tail lobe stream on April 19, 1978, at 0500 UT.

Figure 11. This figure illustrates observations of plasma waves obtained by ISEE-1 and -2.

Figure 12. A schematic illustration of ducted AKR, showing waves with frequencies between 100 and 400 Hz entering a duct and producing discrete encounter signals at ISEE-1, and 400 Hz waves producing diffuse background.

BIBLIOGRAPHIC DATA SHEET

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16. Abstract The ISEE project has made substantial contributions to our knowledge of the magnetosphere during the period of the IMS, especially in the discipline of Space Plasma Physics. This paper reviews results obtained during approximately the first two years of the operation of ISEE-1 and -2, and touches on relevant results of ISEE-3. The ability to control the separation between ISEE-1 and -2, which are in nearly identical orbits, has permitted study of the motion and structure of the bow shock and magnetopause, the boundary layers, and the plasma sheet. Much evidence has been obtained favoring the existence of reconnection and its relevance to the transfer of magnetic flux from the frontside to the rear of the magnetosphere, although not everyone agrees that it is the only important process. The presence of both reflected and accelerated particles has been shown to lead to the development of a foreshock region between the bow shock and the interplanetary magnetic field line tangential to it. In an analogous development, precursors to interplanetary shocks have also been observed. Inside the magnetosphere, ISEE has contributed to our knowledge of plasma waves, and, augmenting work with GEOS, to studies of plasma composition. In the near tail, the boundary layer of the plasma sheet has disclosed interesting phenomena. This progress has largely resulted from the improvement

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