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A Comparison of ULF Fluctuations in the Solar Wind, Magnetosheath, and Dayside Magnetosphere
1. Magnetosheath Morphology

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"Upstream waves," generated in the solar wind upstream of a quasi-parallel bow shock, are believed to be a major source of the Pc 3-4 pulsation activity observed in the dayside magnetosphere. In an attempt to better understand the means by which "upstream wave" energy is transmitted from the solar wind into the magnetosphere, we compared simultaneous data from ISEE 1 and 2 in the upstream solar wind, AMPTE IRM in the subsolar magnetosheath, and AMPTE CCE in the dayside magnetosphere. Our observations indicate that dayside magnetospheric Pc 3-4 pulsation activity and low IMF cone angles are associated with increased turbulence in the subsolar magnetosheath magnetic field (with large amplitude fluctuations both parallel and transverse to the average field direction), and with increased and highly variable levels of energetic magnetosheath particles. Fourier analysis of the magnetic field fluctuations shows broadband increases in wave power from 0.01 Hz to at least 0.5 Hz, but with peak power at Pc 3-4 frequencies; there is no evidence in our data set of narrow-band magnetic field variations in the magnetosheath at these times. Purely compressional waves, which are at times observed in the subsolar magnetosheath, have a somewhat narrower frequency distribution, but are associated with neither upstream wave activity nor magnetospheric pulsations.

INTRODUCTION

It has long been suggested that ULF waves in the ion foreshock in the solar wind upstream of the Earth's bow shock are the source of one class of magnetic pulsation activity observed in the dayside magnetosphere, oftenidentified as Pc 3 pulsations [*Fairfield* 1969; *Greenstadt*, 1972]. Numerous studies have shown that the occurrence of these pulsations on the dayside is correlated to varying degrees with low interplanetary magnetic field (IMF) cone angle, or nearly radial IMF, which is the necessary geometrical condition for allowing turbulent ion foreshock plasmas to convect to the dayside magnetopause (see the recent review papers by *Vero* [1986], *Yumoto* [1986], *Odera* [1986], and *Arnoldy et al.* [1988]).

Many studies have also shown the center frequencies of these waves to vary roughly as f (in mHz) = $6B$, where B is the magnitude of the IMF (in nT). The term "Pc 3" was originally defined strictly on the basis of frequency, to describe pulsations from any source with frequencies in the 25-100 mHz range. Although the IMF magnitude is usually such as to produce pulsations in this range, it is not uncommon to have lower IMF values, with resulting pulsations at frequencies extending into the Pc 4 range. In order to most accurately characterize the pulsations we observe, we will in this paper denote the observed pulsations generically as Pc 3-4 pulsations. Perhaps in the future a more helpful set of names, based on characteristics or physical source rather than strictly on frequency range, will be adopted to replace the current pulsation nomenclature.

The means by which this wave information is transmitted from the upstream solar wind to the magnetosphere is still poorly understood, however. *Fairfield* and *Ness* [1970] reported that magnetic variations in the magnetosheath had a broad amplitude maximum near noon, but with an apparent dawn/dusk asymmetry in amplitude (larger dawnward than duskward of noon), and attributed this spatial distribution to the effects of upstream waves and/or interactions occurring at the bow shock. When the IMF was oriented in its statistically dominant spiral direction, upstream waves, which appeared on field lines that intersected the bow shock, would be convected back across the bow shock in the dawn hemisphere. They also noted that the typical spiral-oriented IMF would be roughly normal to the shock surface (a shock geometry now denoted as quasi-parallel, and understood to be highly unstable) in the dawn sector. *Takahashi et al.* [1984] suggested that because these magnetosheath waves have a relatively broad frequency spectrum, they might be related to the azimuthal multiple harmonic Pc 3-4 resonances observed by various satellites in the outer dayside magnetosphere.

Since the first reports of magnetosheath fluctuations, theoretical studies have concentrated on direct propagation of wave energy [*McKenzie*, 1970; *Verzariu*, 1973; *Kwok and Lee*, 1984], and experimental studies have until very recently focused on locations near the subsolar equatorial magnetopause. Most recently increased attention has been given to the possibility of entry near the polar cusps/clefts.

Verzariu [1973] showed that compressional ULF waves could be transmitted across the magnetopause at a tangential discontinuity, although with typically low (<~1%) efficiency and only close to the subsolar point. A more recent theoretical study by *Kwok and Lee* [1984] indicated much greater power could be transferred (and even amplified) across rotational discontinuities. Such discontinuities are often associated with dayside reconnection sites, but for a nearly radial IMF orientation such discontinuities, and the associated reconnection process, could be expected to occur at high latitudes as well.

Greenstadt [1972], *Wolfe and Kaufmann* [1975], *Greenstadt et al.* [1980, 1983], *Russell et al.* [1983], and *Luhmann et al.* [1986], looking separately at parts of this transmission process from bow shock into the magnetosphere, found evidence supporting the hypothesis that magnetosheath fluctuations were the means by which upstream wave activity was transmitted into the magnetosphere to

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generate Pc 3 pulsations. *Greenstadt* [1972] suggested that because magnetosheath ULF fluctuations are approximately confined to streamlines of magnetosheath plasma flow, excitation of magnetospheric pulsations might be favored when a nearly radial IMF orientation allowed shock-related pulsations to be convected through the subsolar magnetosheath. Later observational reviews by *Greenstadt et al.* [1980] and *Russell et al.* [1983] supported this suggestion, indicating that the connection (or lack of connection) of streamlines containing magnetosheath fluctuations to the magnetopause determines the presence or absence of Pc 3-4 pulsation activity in the magnetosphere. *Luhmann et al.* [1986] found both statistically and on a case by case basis that magnetosheath magnetic turbulence in the subsolar region was enhanced during times of low IMF cone angle. Following this idea, *Luhmann et al.* [1986] pointed out that some of the magnetic field fluctuations observed in the magnetosheath may have been convected there from the quasi-parallel portions of the bow shock and its associated upstream wave region. In addition, although the study of *Luhmann et al.* [1986] involved only magnetic field fluctuations, these authors also called attention to the possible importance of upstream waves and particles for processes involving diffusive entry of magnetosheath plasma into the magnetosphere, magnetic reconnection or merging, and the so-called viscous interactions between the magnetosheath and magnetosphere.

Wolfe and Kaufmann [1975] found empirical support for wave transmission across the magnetopause according to Verzariu's model in magnetopause crossings near the Earth-Sun line, but beyond 30 to 40° from the Earth-Sun line they found too much power inside the magnetopause to fit this model of transmission. *Greenstadt et al.* [1983], using simultaneous data inside and outside the magnetopause from the dual ISEE spacecraft, found one event supportive of the flow of ULF power from the subsolar magnetosheath into the magnetosphere and consistent with the Verzariu model.

Earlier studies of dayside harmonic pulsations at low latitudes in the outer magnetosphere by *Takahashi et al.* [1984] (using pulsation data from ATS 6 and IMF data from IMP 8) and *Engebretson et al.* [1986*b*, 1987] (using pulsation data from AMPTE CCE and IMF data from AMPTE IRM) indicated IMF cone angle control of occurrence of these pulsations. In addition, pulsation studies at high latitudes by a variety of experimenters (*Troitskaya et al.*, 1971; *Bol'shakova and Troitskaya*, 1984; *Plyasova-Bakounina et al.*, 1978, 1986; *Lanzerotti et al.*, 1986; *Engebretson et al.*, 1986*a*, 1989*a*,*b*; *Morris and Cole*, 1987; and *Slawinski et al.*, 1988) have shown varying degrees of control of large amplitude Pc 3-4 activity at near-cusp latitudes by solar wind/IMF properties, as expected for waves originating in the upstream foreshock region. Disagreements as to the extent of control at these latitudes have usually centered on the criterion for selection of narrow-banded or "solar wind-controlled" wave events.

Although enhanced fluctuations of plasma in the magnetosheath have also been known to be associated with a quasi-parallel shock for some time [*Asbridge et al.*, 1978; *Crooker et al.*, 1981], these have apparently not been critically examined as a means of transport of ULF signals toward the magnetosphere. However, recent observations by *Engebretson et al.* [1990*a*] at South Pole Station, Antarctica, at the foot of the nominal dayside cusp/cleft, have directed greater attention to the relation between the magnetosheath particle population and wave events. They found that precipitating electrons with magnetosheathlike energies are often seen at South Pole, with modulation at Pc 3 frequencies, when ground magnetometers see Pc 3 pulsations associated with upstream waves. This observation led *Engebretson et al.* [1990*b*] to propose a model of high latitude entry of these pulsations, based on the idea that modulated electron precipitation is the source of the pulsations observed on the ground at these latitudes.

Asbridge et al. [1978] were the first to note the existence of two distinct states of plasma flow within the magnetosheath, a "quiet" state and a "disturbed" state, the latter characterized by the presence of energetic ions in the range of 3-40 keV. Examination of particle spectra indicated that during "quiet" magnetosheath states both ion and electron spectra were usually stable and reproducible from one 6- or 24-s measurement cycle to the next. However, during the "disturbed" state, which could last from several minutes to many hours, particle spectra fluctuated considerably at all energies. Density, temperature, flow speed, and flow angle all showed large variations during these times. They suggested that the 3-40 keV plasma component characteristic of the disturbed state was (1) accelerated at the bow shock and (2) responsible locally for the observed magnetosheath fluctuations. They were reluctant to label these fluctuations "turbulence" because they had not yet compared the observed plasma fluctuations with variations in the magnetosheath magnetic field. A companion paper by *Gosling et al.* [1978] suggested that the diffuse ion population observed upstream of a quasi-parallel bow shock was the source of the energetic magnetosheath plasma ions.

In a subsequent study *Crooker et al.* [1981] compared ISEE 1 magnetosheath observations with IMF data obtained by ISEE 3, and found that energetic ions were present (absent) in the magnetosheath when plasma at the observation point was convected from a region on the bow shock where the angle between the shock normal and the IMF was less than (greater than) 60°. They interpreted their observations to mean that these ions were convected downstream from the quasi-parallel region of the bow shock.

Although *West and Buck* [1976] had earlier used OGO 5 scanning proton spectrometer data to demonstrate an excellent correlation in the flanks of the dawn and dusk magnetosheath between ions of energy > 100 keV and large amplitude magnetic oscillations, there has apparently been no study of such correlations near the subsolar point. In addition, although several of the studies listed above suggested the validity of early ideas of transmission of upstream wave signals through the magnetosheath and into the magnetosphere, there has been to date no study of correlations between variations in magnetosheath plasma and magnetic field and either the IMF cone angle or dayside magnetospheric pulsations, despite the suggestion by *Asbridge et al.* [1978] that such a study is necessary to fully characterize the "disturbed" plasma state they observed.

In this and a companion paper [*Lin et al.*, this issue] (hereinafter referred to as paper 2) we study simultaneous data from the upstream solar wind, subsolar magnetosheath, and dayside equatorial magnetosphere in an attempt to better understand the properties of the magnetosheath responsible for transmission of upstream ULF wave signals. After presenting the results of a preliminary survey of 48 intervals when AMPTE IRM traversed the Earth's magnetosheath and AMPTE CCE was simultaneously located in the dayside outer magnetosphere, we will in this first paper present a detailed study of two representative intervals. In both cases simultaneous upstream IMF data were available from ISEE 1 and/or 2. The intervals selected will allow us to characterize the magnetosheath both during periods when azimuthally polarized resonant harmonic ULF magnetic pulsations are observed in the dayside outer magnetosphere, and when they are not. Paper 2 will present a more detailed analysis of magnetic field and plasma conditions in the subsolar magnetosheath during these and other periods.

INSTRUMENTATION

The AMPTE satellites were launched August 16, 1984, into near-equatorial highly elliptical orbits as part of a coordinated three-satellite program of active experiments. Two spacecraft, the IRM (ion release module) and UKS (United Kingdom Subsatellite) were placed in 44.3-hour period orbits with apogee at 18.7 R_E. The CCE (Charge Composition Explorer) spacecraft had a period of 15.6 hours and an apogee of 8.8 R_E. The orbits of all three satellites allowed long residence time near local noon during the first six months of the mission. In all cases to be shown in this paper AMPTE CCE remained in the dayside outer magnetosphere. A thorough discussion of the AMPTE mission and instrumentation can be found in the May 1985 issue of the *IEEE Transactions on Geoscience and Remote Sensing*. This issue contains descriptions of the AMPTE CCE magnetometer [*Potemra et al.*, 1985], the AMPTE IRM magnetometer [*Luehr et al.*, 1985], and the AMPTE IRM plasma instrument [*Paschmann et al.*, 1985]. Magnetic field data from AMPTE CCE used in this paper are 6.2-s median samples of data originally obtained at 0.124-s resolution. Magnetic field data from IRM are 1-s averages of data originally obtained at rates of up to 32 samples/s. The AMPTE IRM three-dimensional plasma instrument consists of two symmetrical quadrispherical electrostatic analyzers of the top hat type, one each for ions and electrons. Eight channel electron multipliers are equidistantly spaced at elevation angles of $\pm 11.25^\circ \pm n \times 22.5^\circ$ (for $n = 0, 1, 2, 3$). By rapidly sweeping the analyzer voltage 16 times each spacecraft spin, 30-channel energy spectra in the range from 15 eV to 30 keV for electrons and 20 eV/e to 40 keV/e for ions are obtained every 22.5° in azimuth. These three-dimensional distributions are measured every satellite rotation period, i.e., every ~4.4 s (with the exception of every fifth spin). From each distribution, microcomputers within the instruments compute moments of the distribution functions of ions and electrons: densities in three contiguous energy bands, bulk velocity vector, pressure tensor (from which the temperature is calculated), and heat flux vector.

The two ISEE satellites were launched October 22, 1977 into a highly elliptical orbit with an inclination of 29° and an apogee of 22.6 R_E. Data from the ISEE 1 and/or 2 magnetometer [*Russell*, 1978] used in this paper are 12-s averages plotted every 4 s.

DATA SURVEY

As a preliminary step, we identified 48 events in the first four months of the AMPTE mission (September to December 1984) during which the AMPTE CCE satellite was in a good position to look for dayside pulsations in the magnetosphere while the AMPTE IRM satellite was simultaneously traversing the magnetosheath. These events are characterized by a variety of levels of magnetosheath disturbance and pulsation activity, or lack of it.

A preliminary qualitative comparison of AMPTE CCE and AMPTE IRM data was performed using two-hour plots of AMPTE IRM magnetic field and plasma data and full-orbit color spectrograms of AMPTE CCE magnetic field data. Those passes during which AMPTE IRM data showed large variability in the magnetosheath particle densities and/or the magnetosheath magnetic field were classified as "disturbed," and those passes showing little variation were classified as "quiet." AMPTE CCE spectrograms were independently used to determine whether azimuthally polarized Pc 3-4 (usually harmonic) pulsations were present or absent. Although some AMPTE IRM magnetosheath passes are of several hours' duration, even long, varying events are listed at most twice in this survey.

The results of this comparison are shown in Table 1. The correlation between IRM magnetosheath activity and CCE harmonic activity is very good, but not one-to-one. When magnetosheath conditions are quiet, no Pc 3-4 pulsations are observed in the dayside outer magnetosphere at the location of AMPTE CCE. When the magnetosheath is clearly disturbed, Pc 3-4 pulsations are observed clearly in 22 of 27 cases, and are clearly not observed in only one case. Although we have categorized separately those few passes through the magnetosheath during which the line plots indicated extremely large values of bulk plasma velocity or magnetic field, several "questionable" or uncertain cases were observed in both the AMPTE CCE and AMPTE IRM data. The questionable cases at AMPTE CCE appeared to correlate with disturbed or otherwise extreme magnetosheath conditions, while the questionable cases at AMPTE IRM divided nearly evenly between cases with Pc 3-4 pulsations present or absent.

TABLE 1. Comparison of Subsolar Magnetosheath Activity Measured by AMPTE IRM With ULF Activity in the Dayside Outer Magnetosphere Measured by AMPTE

CCE Observations	IRM Observations			
	Quiet	Uncertain	Disturbed	V_{sw} High or B High
Pc 3-4 absent	7	6	1	1
Uncertain	0	0	4	3
Pc 3-4 present	0	8	22	1

Based on the good preliminary correlation shown above, we selected several representative passes for more detailed study. These events not only exemplify the dominant correlations evident in the preliminary survey but also help to identify the kinds of magnetosheath disturbance which are and are not correlated with Pc 3-4 pulsation activity. Two events are shown in this paper; three additional events were analyzed in detail but are not included here because of space limitations. Pc 3 activity was observed at AMPTE CCE during the entire period of event 1, and during part of event 2. A summary of our observations for all five events is provided in Table 2, and interested readers may request a technical report presenting these other events.

EVENT 1: 2200 - 2400 UT SEPTEMBER 17, 1984

The approximate locations of ISEE 2, AMPTE IRM, and AMPTE CCE satellites for event 1 are displayed in Figure 1. For AMPTE IRM and AMPTE CCE, both located very near the ecliptic plane, we show the equatorial projections of the satellite locations in geocentric solar ecliptic (GSE) coordinates. For ISEE 2, located well below the ecliptic, we plot the radius at the given magnetic local time (i.e., we have rotated the ISEE 2 position vector into the *XY* plane). In this figure the vertical axis points sunward (the GSE *X* direction). The figure includes the full orbit trajectory of AMPTE CCE during the 15.6 h time interval shown at the bottom of the figure, and the portion of the outbound AMPTE IRM trajectory during that same period. Asterisks and crosses indicate the location of AMPTE CCE and AMPTE IRM, respectively, at successive one hour intervals. The figure indicates the location of ISEE 2 (outbound from 20.3 to 20.9 R_E and from 1410 to 1421 local time at approximately -18° magnetic latitude), AMPTE IRM (outbound from 12 to 13 R_E near 1130 MLT), and AMPTE CCE (near apogee at 8.8 R_E near 1300 MLT) during the two-hour IRM magnetosheath crossing event.

The heavy curved traces in Figure 1 represent the equatorial portion of a model bow shock (outer curve) and magnetopause (inner curve), normalized to the position of the actual crossings by AMPTE IRM, based on the formula

$$R = R_0 (1 + \varepsilon) / (1 + \varepsilon \cos(\theta)) \tag{1}$$

where R_0 is the radius at the subsolar point (where $\theta = 0$) and $\varepsilon = 0.7$ for the bow shock and 0.4 for the magnetopause [*Luhmann et al.*, 1986]. Because of the multiple crossings of the bow shock and the magnetopause experienced by AMPTE IRM during this and each of the

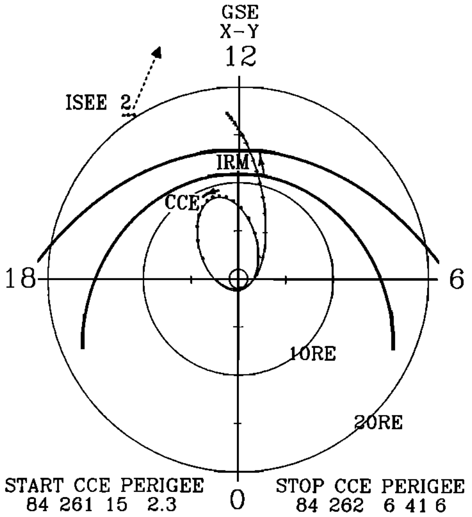

Fig. 1. Approximate satellite locations as projected (for AMPTE IRM and AMPTE CCE) or rotated (for ISEE 2) to the equatorial plane of the geocentric solar ecliptic (GSE) coordinate system during event 1, 2200 to 2400 UT September 17, 1984. The full elliptical orbit of AMPTE CCE during this period is shown from perigee at 1502 UT September 17 (day 84261) to subsequent perigee at 0641 UT September 18 (day 84262), with asterisks denoting the satellite's position at consecutive one-hour intervals. The outbound trajectory of AMPTE IRM during this approximately 16 hour interval is also shown; crosses denote the satellite's position. For both of these satellites the time period of event 1 is highlighted by a parallel line with an arrow. The heavy curved traces represent the equatorial portion of a model bow shock (outer curve) and magnetopause (inner curve), normalized to the position of the actual crossings by AMPTE IRM.

other events studied, the radii as shown should be considered to have an associated error of ±0.5 R_E. Also shown in Figure 1 near the location of ISEE 2 is a vector indicating the average direction of the IMF during this event, as projected in the ecliptic plane. (As will be noted in Figure 3, the IMF was oriented in or near the ecliptic plane throughout this two hour time period.) It is apparent that ISEE 2 is located on IMF field lines connected to a quasi-perpendicular portion of the bow shock, and thus not in the region where upstream waves might be expected to be present. The subsolar region of the shock, however, is expected in this geometry to be the site of a quasi-parallel shock; shocked solar wind plasma from this region is expected to convect into contact with a large portion of the Earth's dayside magnetopause [*Greenstadt*, 1972; *Russell et al.*, 1983].

Plate 1 shows ULF wave data from AMPTE CCE in color spectrogram format from 1800 UT September 17, 1984 to 0200 UT September 18, 1984. From top to bottom the three frequency versus time panels in Plate 1 show the spectral power for the *BR* (radial) component, the *BE* (eastward, or azimuthal) component, and the *BN* (northward) component. Because AMPTE CCE is located near the magnetic equator, the *BN* component is nearly field-aligned. The narrow bottom panel displays variations in field magnitude from the IGRF-80 model value. The three scales at the bottom of the figure denote the *L* shell, magnetic local time, and magnetic latitude of the satellite. In order to compensate for the roughly f^{-2} falloff of background spectral power with frequency, and to take maximum advantage of the available color scale, all the spectrograms presented in this paper are prepared using differenced data. Each individual spectrum in these plots is based on 256 data points. The AMPTE CCE magnetic field data are spaced at 6.2-s intervals, so a single spectrum covers a time period of ~26 min; successive spectra are shifted by 20 points or ~2 min. Spectrograms similar to these, but covering the full 15.6-h period of each orbit of AMPTE CCE, are produced routinely as a means of surveying ULF activity in the AMPTE CCE data set [*Engebretson et al.*, 1987; *Anderson et al.*, 1990].

Weak multiple harmonic resonant pulsations appear in the *BE* component throughout the 8 hour interval shown. We identify the resonant band beginning at 20 mHz near 1800 UT as the second harmonic, and the ~32 mHz band slightly above it as the third harmonic. A weak fundamental resonance can be observed from 1830 to 2030 UT, and several higher order resonances are evident from 1830 to 0200 UT. Note that as the satellite's magnetic latitude decreases through 0, the odd harmonics disappear; this behavior is as expected according to field line resonance models [*Cummings et al.*, 1969; *Cahill et al.*, 1986]. We point out that broadband power appears in the *BR* and especially *BN* components at the same time as harmonic resonances (in the *BE* component). Although this behavior is often seen in the AMPTE CCE data near local noon, and suggests that the azimuthal harmonic resonances and such compressional waves may have a common source, harmonic resonances are not always accompanied by local compressional waves [*Engebretson et al.*, 1987].

Figure 2 shows plasma and magnetic field data obtained by the AMPTE IRM satellite during its outbound traversal of the magnetosheath during event 1. The top three panels in Figure 2*a* show the magnetosheath magnetic field components *Bx*, *By*, and *Bz* in GSE coordinates; the fourth shows field azimuth angle *B-AZ*, defined as arctan(*By*/*Bx*); the fifth the elevation angle *B-EL*, defined as arcsin(*Bz*/|*B*|); and the sixth the magnitude |*B*|. The top three panels in Figure 2*b* show, respectively, the density of ions per cm^3 from 20 eV/e to 40 keV/e (*Np*) and density of energetic ions (≥8 keV/e) (*Nph*) and the plasma temperature (*Tp*) in units of 10^6 K. The lower three panels display the azimuth angle, elevation angle, and magnitude of the magnetosheath bulk velocity (*VpAZ*, *VpEL*, and *Vp*, respectively, in degrees and km/s). The plot scales are chosen to be uniform for both of the events considered in this paper.

The magnetosheath magnetic field (Figure 2*a*) shows substantial fluctuations in all three components as well as in azimuth, elevation angle, and magnitude. Because of the 360° periodicity of the azimuth angle, we have utilized a plot wrapping algorithm to display all angular changes using steps of 180° or less. Even with this routine, which serves to eliminate large apparent angular excursions caused by crossings of the plot extrema, the azimuth angle exhibits numerous extremely rapid large variations, often in association with intervals of largest fluctuation (> 40 nT) in each of the individual components (top three panels). Detailed plots show that such large swings occur on time scales ranging from 3 s to over 30 s. Note that the similarly rapid and large fluctuations in the elevation angle are correct as plotted, without wrapping.

The magnetosheath plasma data shown in Figure 2*b* also indicate large variations in several parameters. The bulk plasma density (top panel) exhibits up to 100% fluctuations during this two-hour interval, but the more energetic ions and plasma temperature show smaller variations. The plasma velocity shows considerable variations in magnitude, and variations in direction that, although large, are not as large as those of the magnetic field. Although one might expect AMPTE IRM to be located close to a region of nearly stagnant magnetosheath flow at the beginning of this interval (near the magnetopause), extremely low velocities are evident at times throughout the two-hour magnetosheath crossing. Comparison of Figures 2*a* and 2*b* indicates simultaneous increases in variability in all panels near 2230, 2245, and 2315 UT. The connection between these variations will be addressed in greater detail in paper 2.

A Fourier spectrogram of the 1-s averaged AMPTE IRM magnetic field component data is shown in Plate 2. The irregular, often spikelike nature of the waveforms seen in Figure 2*a* causes broad-

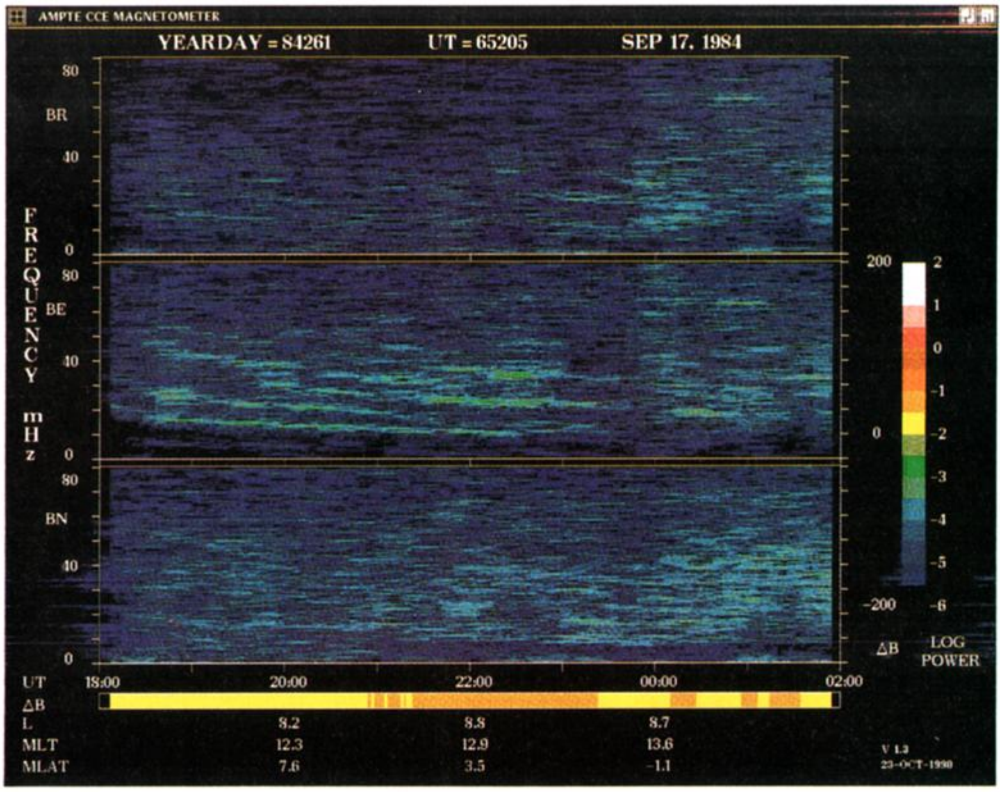

Plate 1. Three component dynamic power spectrogram of AMPTE CCE magnetic field data from 1800 UT September 17, 1984 to 0200 UT September 18, 1984. Field components shown are radial (*BR*), azimuthal, or magnetically eastward (*BE*), and parallel to the Earth's dipole axis, or magnetically northward (*BN*). The bottom colored panel represents ΔB, the difference in field magnitude between the observed total field and the value determined from the IGRF-80 model. Apogee is at the center of the plate.

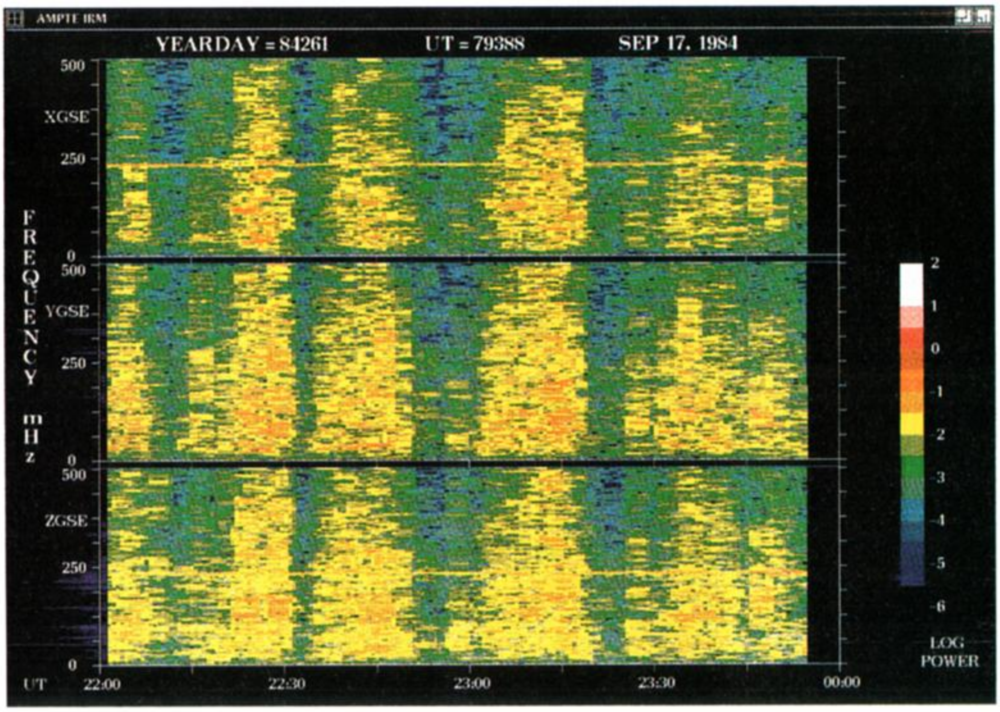

Plate 2. Three component dynamic power spectrogram of 1-s averaged magnetic field data from the AMPTE IRM satellite from 2200 to 2400 UT September 17, 1984. Field components shown are in the GSE coordinate system.

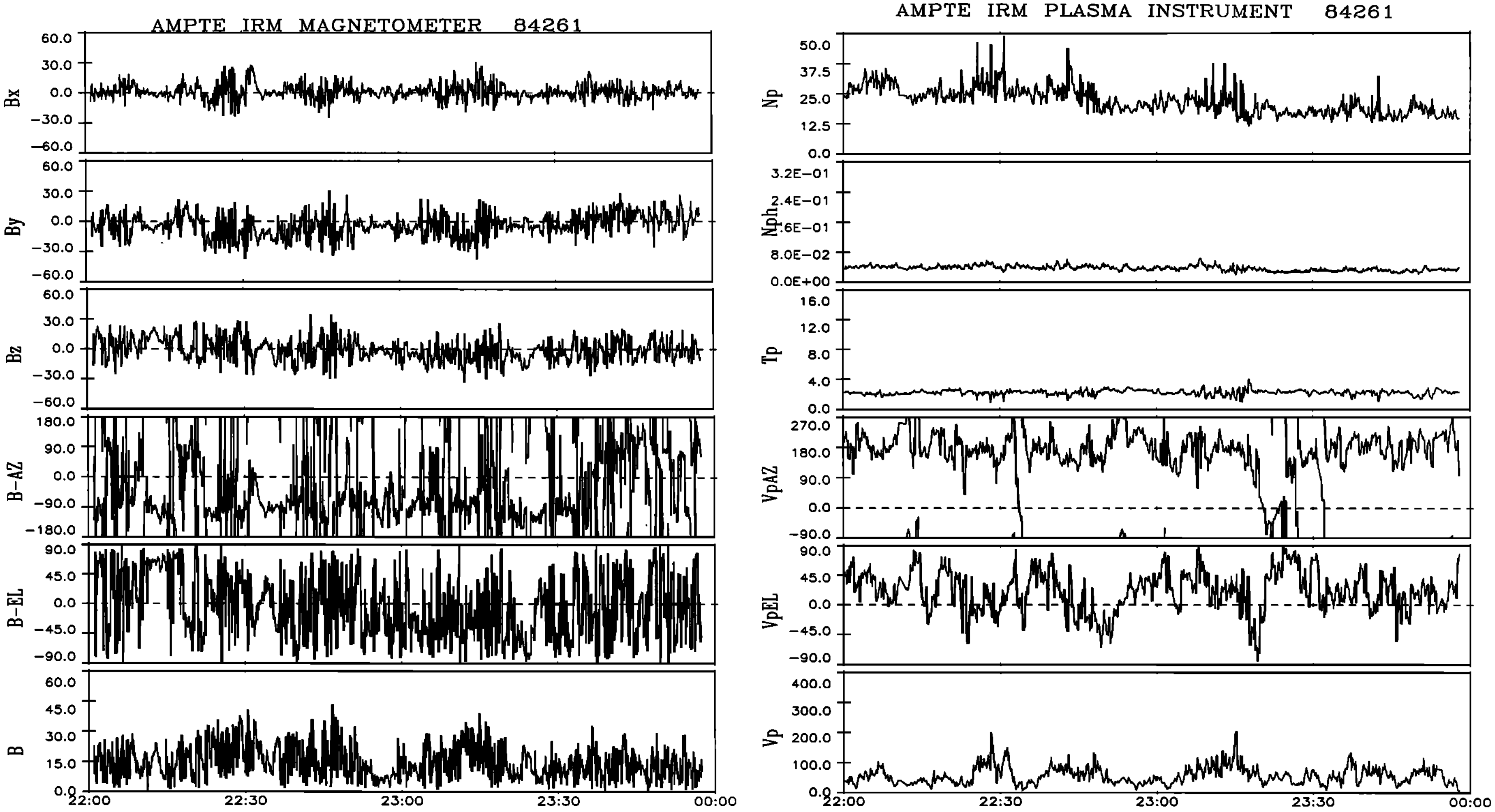

Fig. 2. Magnetosheath particle and field data from the AMPTE IRM satellite during event 1, 2200 to 2400 UT September 17, 1984 (day 261). (*a*) From top to bottom the panels are the *Bx*, *By*, and *Bz* magnetic field components in nanoteslas in a GSE (geocentric solar ecliptic) coordinate system, magnetic field azimuth angle *B-AZ* and elevation angle *B-EL* in degrees, and field magnitude *B* (in nT). All data shown are 1-s averages. (*b*) From top to bottom the panels are bulk proton density *Np* and keV proton density *Nph* (both in cm^{-3}); proton temperature *Tp* (in 10^6 K); proton bulk velocity azimuth angle *VpAZ* and elevation angle *VpEL* (in degrees), and bulk velocity *Vp* (in km/s) in a GSE coordinate system. All data shown are 4.4-s samples, with every fifth data point missing.

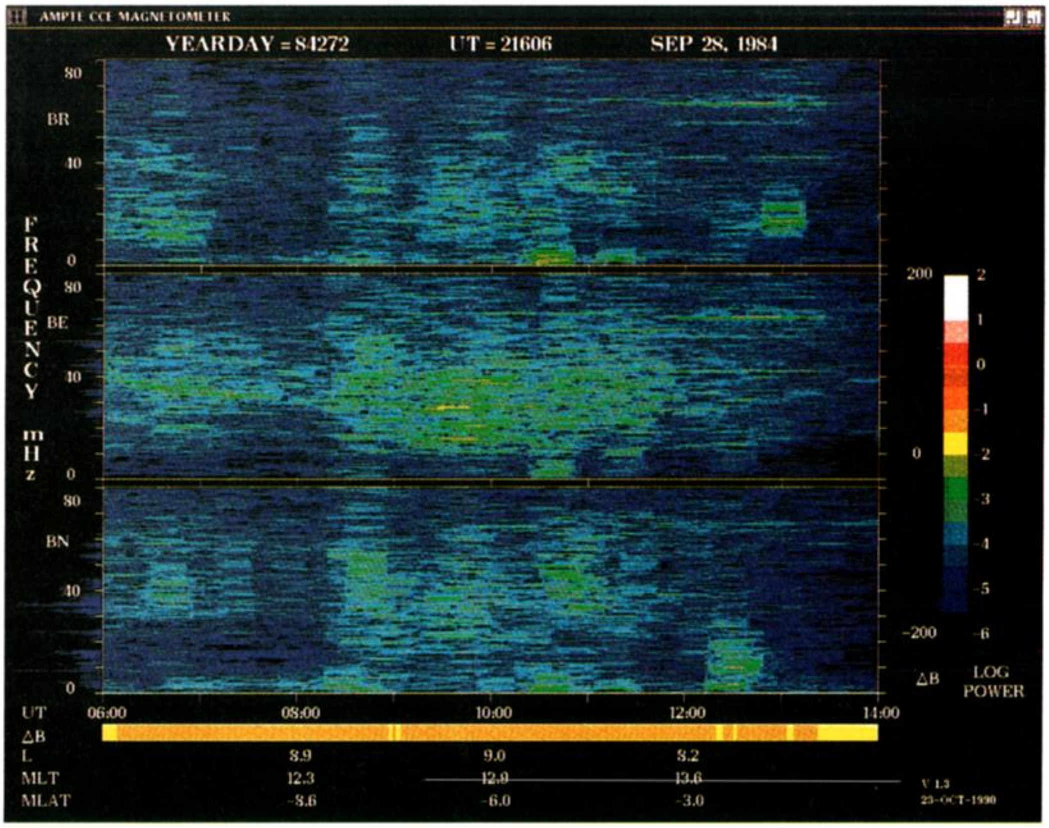

Plate 3. Three component dynamic power spectra of AMPTE CCE magnetic field data from 0600 to 1400 UT September 28, 1984, as in Plate 1.

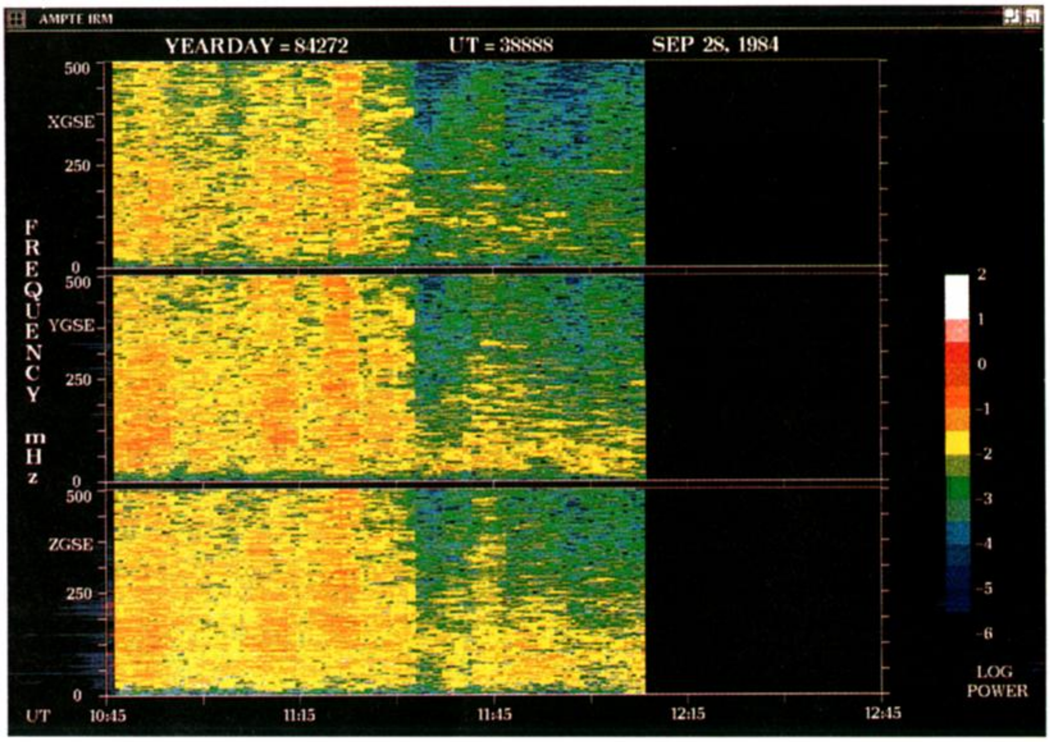

Plate 4. Three component dynamic power spectrogram of 1-s averaged magnetic field data from the AMPTE IRM satellite during event 2, from 1045 to 1215 UT September 28, 1984, as in Plate 2.

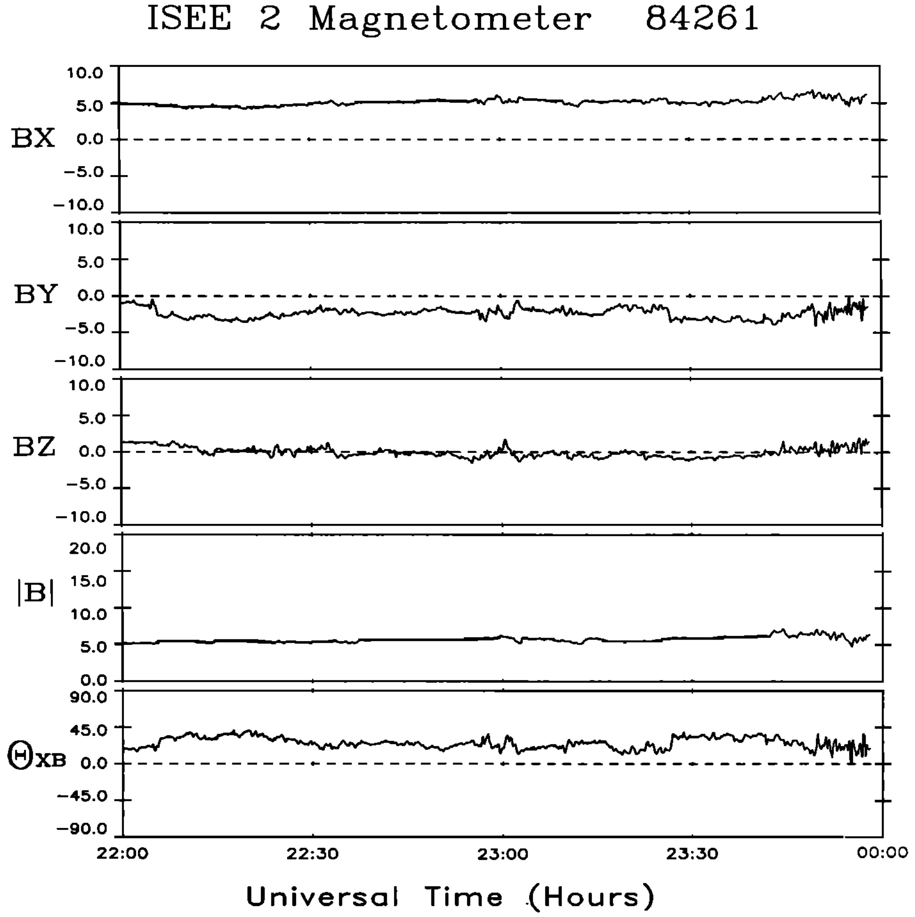

Fig. 3. Magnetic field data from the ISEE 2 satellite in the solar wind during event 1, 2200 to 2400 UT September 17, 1984. The top three panels show field components in GSE coordinates; the fourth panel shows field magnitude, and the fifth panel shows the IMF cone angle.

band, relatively featureless enhancements of power in each of the spectrogram panels, with frequencies ranging from ~ 10 mHz up to the 500 mHz Nyquist limit. Individual spectra in this figure are again calculated from 256 data points, in this case covering ~4 min, and successive spectra are shifted by 20 s.

Figure 3 shows interplanetary magnetic field (IMF) data from ISEE 2 in GSE coordinates during event 1. From top to bottom the panels shown are Bx, By, Bz, $|B|$ (total field), and the IMF cone angle ($\cos^{-1}(Bx / |B|)$). The IMF magnitude and Bx and Bz components remain nearly steady during the interval shown. Despite modest variations in the By component, the cone angle remains below 40° throughout. The increased level of fluctuations evident after 2350 UT is consistent with the rotation of the IMF to a larger Bx component and a less negative By component occurring from 2350 to 2400 UT. The fluctuations are most likely upstream waves, indicating that beginning at this time ISEE is located in the ion foreshock region.

Based on the observed average IMF magnitude of 5 to 6 nT, we calculate the expected center frequency of upstream waves during event 1 to be 30 to 36 mHz. These frequency values lie in the range of Pc 3-4 pulsations observed in the dayside magnetosphere (from ~10 to 50 mHz, see Plate 1) and coincide roughly with the lowest frequencies of enhanced power shown in Plate 2. Because the differencing used in preparing the spectrograms removes an f^{-2} falloff in frequency, the bottom of the range of frequencies with enhanced power in fact contains the greatest spectral power in the magnetosheath during these intervals. Line spectra produced without differencing (not shown) confirmed that the peak spectral power in the magnetosheath during these intervals occurs in a broad range from ~10 to 100 mHz.

As was pointed out by *Engebretson et al.* [1989*b*,1990*b*], Pc 3-4 pulsations at cusp/cleft latitudes associated with harmonic resonances have a band-limited rather than a narrow-band character, with a roughly ±50% bandwidth about the center frequency. The ~10 mHz lower range of Pc 3-4 harmonic pulsations observed in the dayside magnetosphere agrees quite well with the lower range of frequencies with enhanced spectral power observed in the magnetosheath magnetic field (Plate 2), but the upper range of enhanced power appears to extend to higher frequencies in the magnetosheath than in the magnetosphere.

EVENT 2: 1045 - 1215 UT SEPTEMBER 28, 1984

Figure 4 shows the equatorial projections of the orbits of ISEE 1, AMPTE IRM, and AMPTE CCE from 1045 to 1215 UT September 28, 1984, as in Figure 1. During this event AMPTE IRM was inbound in the magnetosheath near 1400 MLT, crossing the bow shock near 12.5 R_E and the magnetopause near 10 R_E. AMPTE CCE was near apogee but inbound between 1310 and 1340 MLT, and ISEE 1 was situated in the upstream solar wind, inbound from 18.2 to 17.4 R_E and from 1444 to 1453 local time at approximately -17° magnetic latitude.

In this figure we have drawn two vectors to represent the approximate IMF direction during the first part of the event (solid line) and during the second part of the event (dashed line). The vectors suggest

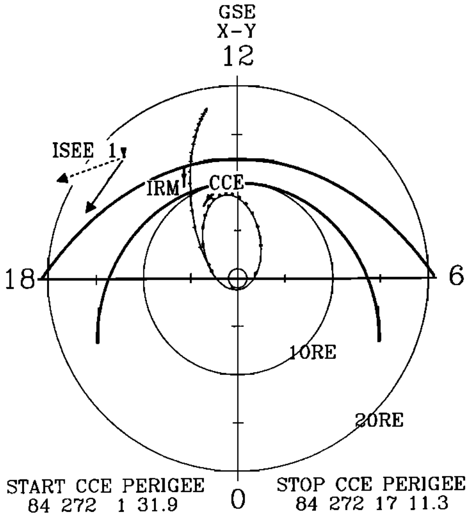

Fig. 4. Approximate locations of the ISEE 1, AMPTE IRM, and AMPTE CCE satellites during event 2, 1045 to 1215 UT September 28, 1984, as in Figure 1.

that during the first part ISEE 1 was located on IMF field lines connected to a quasi-perpendicular portion of the bow shock, while the subsolar region of the bow shock was the site of a quasi-parallel shock. During the second part the IMF field lines at ISEE 1 were not at all connected to the bow shock, and the subsolar bow shock was the site of a quasi-perpendicular shock.

The AMPTE CCE magnetic field data shown in Plate 3 indicate relatively continuous Pc 3 wave activity in the *BE* component from 0830 to 1130 UT, with some power continuing until 1145 UT. Broadbanded power with slightly higher frequencies is evident in the *BN* component from 0830 to 0900, from 0915 to 1000, and from 1035 to 1105 UT. Long-period compressional power increased from 1215 to 1245 UT, but no transverse wave activity was observed to accompany these compressional fluctuations.

Figure 5 shows plasma and magnetic field data obtained by the AMPTE IRM satellite from 1045 to 1215 UT, during its inbound traversal of the magnetosheath during this event. The magnetic field (Figure 5*a*) was considerably more disturbed before 11:35 than after. As was the case for event 1, fluctuations of similar amplitude occurred in all components. Increased magnetic field magnitudes and almost purely compressional waves occurred during most of the second half of the period shown, even during a gradual rotation of the field from eastward (near 1140 UT) to northward (near 1155 UT) and back to eastward (near 1205 UT). After 1135 UT either or both the *By* and *Bz* components of the field were often quite far from zero, while the *Bx* component was consistently smaller and showed much less variation. In contrast to event 1 and the first half of this event, the azimuth angle was nearly constant during the second half of event 2, and fluctuations in the elevation angle were considerably smaller.

Magnetosheath plasma data for event 2 are shown in Figure 5*b*. The traces in all six panels were again more disturbed prior to 1135 UT than afterward. The first half of the interval also coincided with a period of significantly elevated densities of > 8 keV ions, consistent with the presence of such ions during event 1 in association with similarly disturbed conditions. The density of energetic ions dropped suddenly at 1132 UT, and showed only two very short-lived increases thereafter. Fluctuations in the plasma density, temperature, and bulk velocity vector remained at low to moderate levels after 1132 UT except for a brief interval near 1145 UT, despite the sudden northward reorientation of the magnetosheath field near 1207 UT. The bulk velocity was considerably higher during this event than during event 1 (and most other events studied, regardless of disturbance level), perhaps in part because AMPTE IRM was during this event located somewhat farther from the Sun-Earth line and the magnetosheath flow stagnation region.

The dynamic spectrogram of the components of the magnetosheath magnetic field (Plate 4) indicates patterns very similar to those of event 1 during the interval of disturbed conditions. Spectral power was enhanced from ~15 mHz to at least 500 mHz until 1133 UT, at which time it decreased abruptly by about two orders of magnitude at most frequencies. More narrow-band power enhancements appeared between 30 mHz and ~150 mHz, with a broad peak near 60 mHz, in the *By* and *Bz* components. As expected from Figure 5*a*, this power was strongest in the *Bz* component near 1150 UT, and strongest in the *By* component near 1200 UT.

ISEE 1 data for this 1.5 h period are shown in Figure 6. The field was reasonably quiet throughout the interval, but changed in steps from being primarily radial (negative *Bx* component dominant) to transverse (positive *By* component dominant). Excursions in the *Bz* component, if delayed by ~8 min, appear to closely match changes in the *Bz* component observed at AMPTE IRM. The IMF cone angle gradually changed from a value favorable for generating upstream waves at the nose of the bow shock (155°) at 1045 to one unfavorable for such waves (110°) at 1115 UT. After a ~12 min return to cone angles above 140° from 1115 to 1125 and an even shorter increase near 1137 UT, the cone angle was unfavorable until 1205 UT, when two sudden reorientations and a small amplitude square wave in field magnitude preceded another brief (10 min) interval of favorable cone angle. The intervals of favorable cone angle (1045 to 1125 UT and near 1145 UT) match, with an ~8 min time delay, the times at which AMPTE IRM observed enhanced densities of energetic ions and strong transverse fluctuations in the magnetic field and the times when increased azimuthal activity was evident at AMPTE CCE. The solar wind reorientations at 1205 UT appear to match the increased transverse magnetic field fluctuations, fluctuating bulk velocity vector, and increased density of energetic ions at AMPTE IRM from 1210 to 1215, as well as the short burst of compressional pulsation activity at AMPTE CCE.

The observed IMF magnitude again ranged from 5 to 6 nT, suggesting that the expected center frequency of upstream waves during event 2 was from 30 to 36 mHz. These frequency values again lie near the center of the range of Pc 3-4 pulsations observed in the dayside magnetosphere (from ~10 to 50 or 60 mHz) as shown in Plate 3. The lowest frequency of enhanced power shown in Plate 4, approximately 20 mHz, is also consistent with this center frequency.

As a final step in displaying the magnetosheath data, we prepared dynamic Fourier spectrograms of plasma data for each event in addition to the magnetic field data already displayed in Plates 2 and 4. In each case associated with Pc 3-4 pulsations we also observed broadband excitations in the plasma parameters, with fluctuations from ~10 mHz up to their 112 mHz Nyquist rate. In none of the events studied did we observe a narrow-band frequency enhancement such as might be expected for a band-limited upstream wave source [*Russell et al.*, 1987] or as observed below the dayside cusp [*Engebretson et al.*, 1990*a*]. Because of the frequent time discontinuities in the plasma data (every fifth point missing), we took two additional steps in analyzing the spectrum of these data sets. In the first approach, we used a linear interpolation routine to fill in the missing data points, and then used a standard Fourier transform algorithm. In the second approach, we used a Lomb-Scargle technique [*Press and Teukolsky*, 1988], which does not require the use of continuously sampled time series. Using both approaches we again found very broadband spectral features in the differenced data, and no sign of sharply band-limited signals.

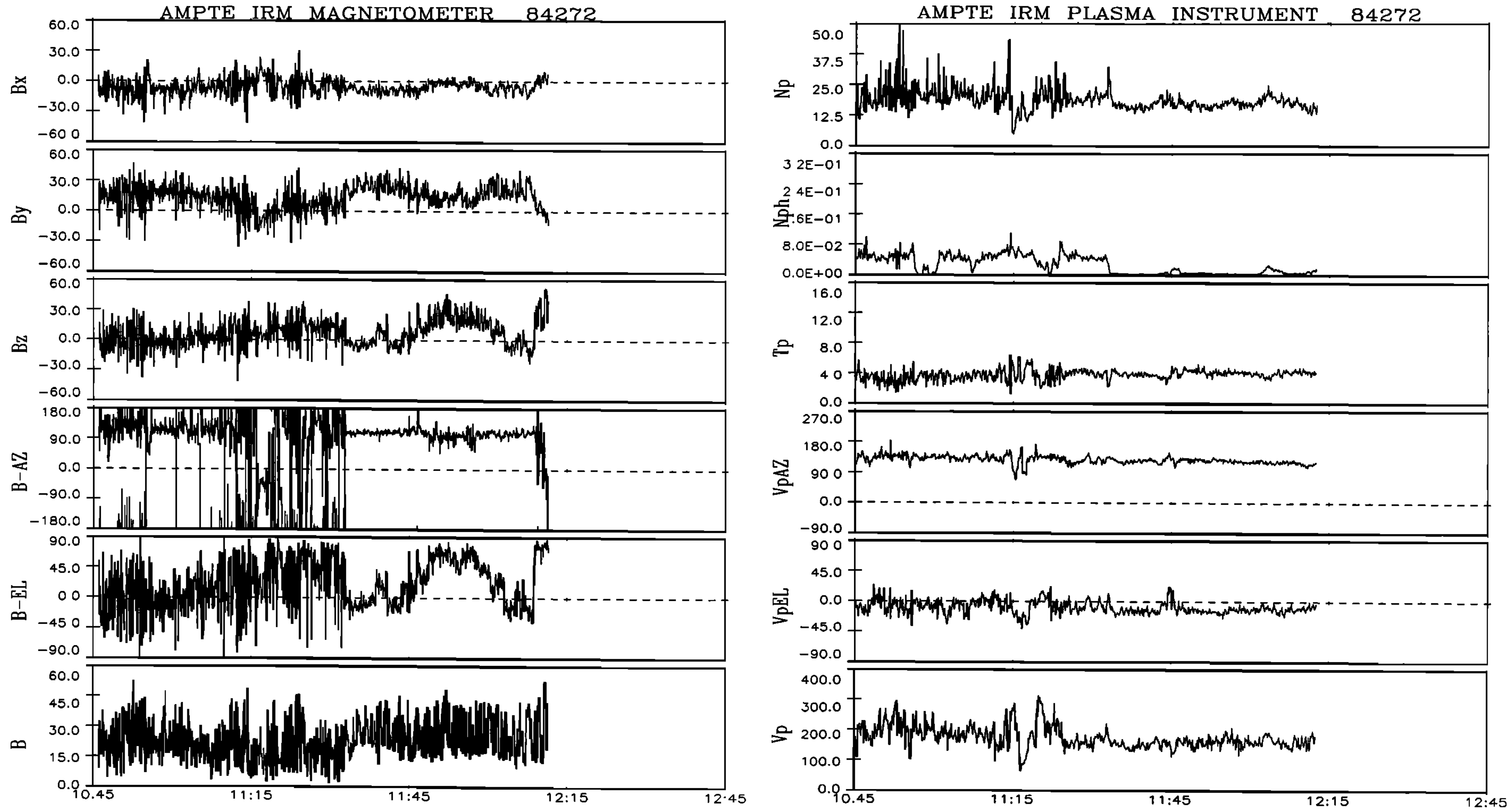

Fig. 5. Magnetosheath particle and field data from the AMPTE IRM satellite during event 2, 1045 to 1215 UT September 28, 1984 (day 272) as in Figure 2.

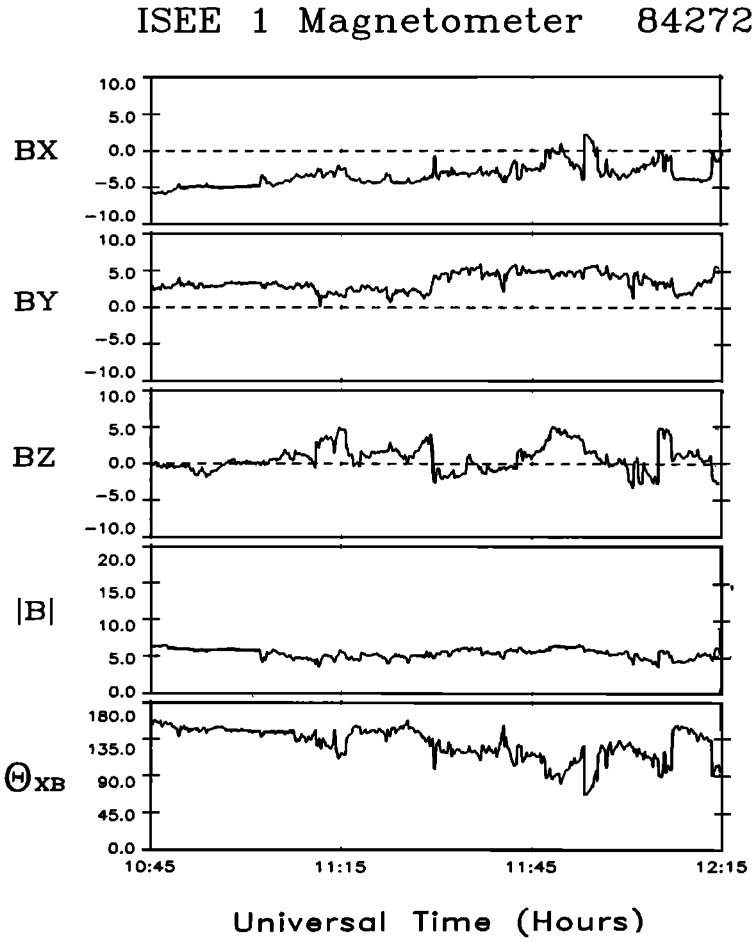

Fig. 6. Magnetic field data in GSE coordinates from the ISEE 1 satellite in the solar wind during event 2, 1045 to 1215 UT September 28, 1984, as in Figure 3.

As noted above, however, a flat spectral response in the color spectrograms indicates a falloff of f^{-2} in spectral power. Thus although spectral analysis of both events indicated enhancements of spectral power from ~10 mHz to at least the Nyquist frequency during times that Pc 3-4 pulsations were observed in the dayside magnetosphere, the peak spectral power during these periods was near the bottom of the region of spectral enhancements, that is, in the Pc 3-4 frequency range.

Table 2 contains a summary of the key parameters for the five events studied in detail. The IMF cone angle, and its associated categorization of the shock geometry in the subsolar bow shock region as quasi-parallel or quasi-perpendicular, appears to control both the character of the magnetic pulsations in the dayside magnetosphere and the characteristics of magnetic field and plasma parameters in the subsolar magnetosheath. Large, omnidirectional fluctuations in magnetosheath magnetic fields and greatly increased fluxes of energetic magnetosheath ions are clearly associated with low cone angles and with the presence of dayside multiple harmonic pulsations.

DISCUSSION

Two separate but related models have been proposed to explain the connection between Pc 3-4 wave activity in the dayside magnetosphere and the occurrence of low cone angles and associated foreshock waves in the upstream solar wind [*Greenstadt*, 1990]. In the first, pulses, waves, or turbulence generated as part of a quasi-parallel shock are convected against the Earth's magnetopause. As this spatially structured magnetosheath plasma convects along the magnetospheric boundary, it in some way perturbs the magnetopause and transfers information into the magnetosphere. In the second model, waves in the foreshock are transmitted (perhaps with modifications) through the shock, magnetosheath, and magnetopause into the dayside magnetosphere. The studies of *McKenzie* [1970], *Verzariu* [1973], and *Kwok and Lee* [1984] referred to in the introduction have focused on this mode of transmission through the magnetopause.

The most efficient wave coupling is empirically associated with conditions in which the subsolar point of the bow shock is a site of quasi-parallel shock geometry [Greenstadt, 1972; Greenstadt et al., 1980; Russell et al., 1983]. The nature of the streamline flow of the shocked solar wind dictates that under such conditions plasma from this region will bathe a large portion of the dayside magnetopause. Although this geometrical condition is clearly supportive of the first model, the high speed of magnetosheath plasma flow makes it very difficult to separate spatial from temporal structure, and thus makes it difficult to distinguish these models on purely geometrical grounds.

A further experimental difficulty is that, according to gas dynamic models of solar wind—magnetopause interactions, the only streamline that contacts the magnetopause is the one that actually passes through the stagnation point [*Russell et al.*, 1983; *Luhmann et al.*, 1986, and references therein]. This streamline subsequently coats the entire surface of the magnetosphere. Hence the location of AMPTE IRM during the two events presented here is not optimal; if the gas dynamic model holds during these turbulent conditions, AMPTE

TABLE 2: Summary of Observations Presented in This Paper.

Solar Wind	*Magnetosheath*	*Magnetosphere*
	Event 1	
Cone angle mostly < 40° (Quasi-parallel shock at nose)	Large B fluctuations 10-500 mHz in all components, centered near 0; B_0 reduced; Energetic ions	Weak multiple harmonics in *BE*; Broadband in *BN*
	Event 2a (1045-1130 UT)	
Cone angle mostly > 135° (Quasi-parallel shock at nose)	Large B fluctuations 15-500 mHz in all components, centered near 0; B_0 reduced; Energetic ions	Harmonics in *BE*; Broadband in *BN*
	Event 2b (1130-1210 UT)	
Cone angle mostly < 135° (Quasi-perpendicular shock at nose)	Large compressional fluctations in B; B_0 increased; Few energetic ions	No harmonics in *BE*; *BN* at background
	Event 3 (Day 252, 1984, 1500-1700 UT)	
Cone angle mostly > 45° (Quasi-perpendicular shock at nose)	Small B fluctuations 125-500 mHz in all components; Large B_0 mainly in By, Bz, with steady azimuth angle; Few energetic ions	No harmonics in *BE*; Monochromatic in *BR*; *BN* at background
	Event 4a (Day 283, 1984, 1215-1240 UT)	
	Large B fluctuations 15-500 mHz in all components, centered near 0; B_0 reduced; Very energetic ions	Strong harmonics in *BE*; Broadband in *BN*
	Event 4b (Day 283, 1984, 1245-1345 UT)	
	Large compressional fluctuations in B, 30-180 mHz; B_0 increased; Energetic ions reduced	Harmonics gradually diminish in BE; *BN* at background
	Event 5 (Day 254, 1984, 1235-1400 UT)	
Cone angle < 35° (Quasi-parallel shock at nose)	Large B fluctuations 10-500 mHz in all components; Energetic ions	Strong harmonics in *BE*; Broadband in *BR*, *BN*; Monochromatic in *BR* at end

IRM did not sample the body of plasma that transmits information about upstream waves to the magnetosphere. In most cases the plasma it samples is more likely to be deflected around the magnetopause without ever coming very near to the boundary. To the extent that quasi-parallel or quasi-perpendicular shock geometry exerts significant control over magnetosheath characteristics "near" the subsolar point, however, the AMPTE IRM data may still provide significant information about the Earthward flow of wave information from a shock-related source.

Our finding that purely compressional waves are not associated with magnetospheric Pc 3-4 activity is consistent with the recent observations by *Hubert et al.* [1989] and earlier workers that "mirror" waves are associated with a quasi-perpendicular bow shock structure. We believe it is also significant that the absolute level of magnetic field fluctuations (ΔB) in the magnetosheath is no larger when the IMF cone angle is low and magnetospheric Pc 3-4 waves are observed than during times when compressional waves are observed. It thus appears that the magnitude of magnetic variations in the subsolar magnetosheath is not the critical factor in transmitting upstream wave power into the dayside magnetosphere. Our observations suggest that either the presence of transverse magnetic field oscillations or the distinctively different morphology of the plasma, and especially its energetic component, may be the key factor.

In paper 2, a more quantitative study of these intervals, we report that greatly increased and fluctuating kinetic beta and thermal beta, disordered magnetic fields, and variability in kinetic and total pressure in the magnetosheath are associated with low IMF cone angles and simultaneous harmonic Pc 3-4 activity in the dayside magnetosphere. The increase in magnitude and variability of the kinetic beta values suggests that the subsolar magnetosheath plasma may exert variations in dynamic pressure on the magnetopause (possibly in quite localized regions) during these times. In addition, the very large thermal beta values, often >> 1, indicate that during these times the "frozen-in" plasma assumption may be invalid, at least for the substantial energetic tail of the magnetosheath plasma distribution. Although a more detailed analysis must be done to confirm it, the high thermal beta values observed lend some support to the suggestion by *Asbridge et al.* [1978] that downstream from a quasi-parallel shock energetic magnetosheath particles determine the local magnetic field characteristics, and not vice versa. This could also explain why the magnetic field fluctuations we observe are broadband, rather than harmonic or at least narrow-band. These observations also suggest that plasma processes at the magnetosheath/magnetopause/boundary layer interface may be more complicated during these times than is assumed by many models of such boundary processes.

Gosling et al. [1989] and *Thomsen et al.* [1990] reported that the ion distributions in the magnetosheath downstream from a quasi-parallel shock alternated between a cooler, denser type and a hotter, less dense type. Both types of distributions could also be observed during shock ramp crossings, suggesting to these authors that they are formed alternately as part of the unsteady, cyclic nature of the quasi-parallel shock itself, and are not related one to the other via any process of downstream evolution. The cyclic nature of the quasi-parallel shock has also been suggested by the numerical simulations of *Burgess* [1989] and *Thomas et al.* [1990]. The periodicity of these alternating magnetosheath distributions, from 1 to a few upstream ion gyroperiods, matches the periodicity of shock re-formation found in the numerical simulations. The fact that these variations roughly match the period of upstream waves (and of the center frequency of related Pc 3-4 activity in the magnetosphere) suggests that the quasi-parallel shock itself might serve to spread out the spectral power of the upstream waves, resulting in the broad spectral features evident in the magnetic field spectrograms shown in Plates 2 and 4.

The high latitude entry mechanism proposed by Engebretson et al. [1990*b*] to explain solar wind control of dayside Pc 3-4 pulsations is based on the idea that momentum or pressure variations in the magnetosheath serve to transfer the "wave" information to the high latitude ionosphere by causing modulated particle precipitation and/or modulated Birkeland currents in the cleft/boundary layer. Although this idea has received almost no direct theoretical attention, recent theoretical studies of the ground signature of flux transfer events have focused attention on the impact of variations in solar wind dynamic pressure. *Southwood and Kivelson* [1990], using an MHD approach, predicted field-aligned currents with temporal variations reflecting the time dependence of impinging solar wind pressure variations. They also acknowledged the need to include more realistic models of the effects of magnetosheath plasma variations in their models. In a related paper *Kivelson and Southwood* [1990] noted that such pressure variations contribute nonlinear transport of momentum from the solar wind into the magnetospheric cavity. Although these models were intended to apply most directly to longer period pressure perturbations, in the Pc 5 period range, our observations suggest their model may be applicable to fluctuations generated at a quasi-parallel shock as well.

The data presented here may also be of interest to those studying the process of dayside reconnection. Observations at South Pole by *Engebretson et al.* [1990*a*] have shown that the occurrence and amplitude of Pc 3-4 pulsations have little if any dependence on the sign of IMF Bz or, when the IMF is radial, on the sign of Bx. According to conventional concepts of magnetopause reconnection this would seem to rule out any role for reconnection, and hence the *Kwok and Lee* [1984] mechanism, in transmitting upstream wave signals into the magnetosphere. However, in the cases we have studied a large (often 30 nT or more), rapidly fluctuating Bz component of the magnetosheath field occurs specifically when the IMF is primarily radial, regardless of the sign of the small upstream Bz component. Although the duration of the large southward magnetosheath fields thus produced is usually quite short (typically 1 min or less), available data cannot rule out a possibly significant role for intermittent reconnection, and hence the Kwok and Lee mechanism, in the process of wave transmission. The recent suggestion by *Nishida* [1989] that random, patchy (transient and localized) reconnection can populate the low-latitude boundary layer (LLBL) for all IMF Bz orientations can be cited as indirect support for this conjecture. Nishida's suggestion implies a thicker LLBL for $Bz>0$, as observed, and observations that the LLBL consists of blobs with distinct boundaries also suggest a patchy sort of filling process.

SUMMARY

We have shown two intervals of simultaneous observations in the solar wind, magnetosheath, and dayside outer magnetosphere to illustrate the apparent connection between IMF orientation, the presence or absence of dayside Pc 3-4 resonant harmonic pulsations within the magnetosphere, and variations in magnetosheath fields and plasma. We have found, both in a preliminary statistical study and on a case-by-case basis, that IMF cone angles which allow a quasi-parallel shock to form at the subsolar bow shock are well correlated with extremely turbulent magnetosheath plasma and fields, and with simultaneous excitation of harmonic Pc 3-4 pulsations in the dayside outer magnetosphere. These results confirm and extend relationships inferred from numerous previous satellite- and ground-based studies.

Although we have not found any magnetosheath parameter which exhibits a narrow-band oscillation at the frequency inferred for upstream waves, and could thus provide a "direct link" between band-limited upstream waves and similarly band-limited Pc 3-4 resonant harmonic waves, we have found relatively broadband enhancements of power in both magnetic fields and in plasma parameters in the subsolar magnetosheath, with peak power at frequencies near the center frequency expected for the upstream waves. Although we believe that it is probable that such broadband enhancements are in some way responsible for the transmission of wave information, the means by which the upper frequencies of this enhanced signal are attenuated remains to be determined.

We have also been able to confirm and extend earlier observations of the character of magnetosheath field and plasma perturbations during the times such waves occur. We have found (1) highly disordered magnetic fields, with large fluctuations in all three components, with large, rapid variations in both magnitude and direction and very broadband frequency structure; (2) enhanced fluctuations in all bulk plasma parameters; and (3) enhanced densities of energetic (> 8 keV) ions. With the exception of the third property during one case (not shown), none of these is observed in any of the events studied during times pulsations are absent. In two of the five cases (one shown in this paper) large, purely compressional waves occurred in the magnetosheath magnetic field, but simultaneous dayside Pc 3-4 activity was not observed.

Despite nearly two decades of study, there is as yet no comprehensive explanation of the means by which band-limited upstream wave signals cause similarly band-limited pulsations in the dayside magnetosphere, in part because attention appears to have been focused on wave transmission rather than on the convection of disturbed magnetosheath plasma. Only recently have theoretical analyses begun to focus on the importance of varying magnetosheath plasmas for the transfer of perturbation signals into the magnetosphere. This is clearly an area that needs further investigation. Finally, although we have for the first time compared simultaneous data in the solar wind, subsolar magnetosheath, and magnetosphere, we have not found cases during which we were clearly sampling the magnetosheath plasma volume that actually carried upstream wave information to the magnetopause. The result is that a definitive observational study remains to be done, possibly using CLUSTER and other satellites to be launched as part of the International Solar-Terrestrial Program.

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