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FLANK SOLAR WIND INTERACTION

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Technical Summary

Introduction

In this report we will summarize the results of the work performed under the "Flank Solar Wind Interaction" investigation in support of NASA's Space Physics Guest Investigator Program. While this investigation was focused on the interaction of the Earth's magnetosphere with the solar wind as observed by instruments on the International Sun-Earth Explorer (ISEE) 3 spacecraft, it also represents the culmination of decades of research performed by scientists at TRW on the rich phenomenology of collisionless shocks in space. For the opportunity to work in this field we are all indebted to the late Dr. Frederick L. Scarf.

The ISEE 3 spacecraft traversed many regions of unique importance to space physics during its long mission, and for this investigation we chose to examine several aspects of the solar wind interaction region on the far flanks of the bow shock. These studies encompassed the foreshock and magnetosheath as well as the shock itself. Most of our effort involved analysis of data from the ISEE 3 plasma wave investigation (PWS) [Scarf et al., 1978], but also included correlative examinations of magnetometer [Frandsen et al., 1978] and plasma analyzer data [Bame et al., 1978].

The uniqueness of the solar wind interaction on the far flanks manifests itself in many forms. The primary reason for interest is that this region has seldom been encountered by spacecraft and the data obtained has been little analyzed. The ISEE 3 exploration of this region in 1982 and 1983 (prior to injection into a heliocentric orbit to intercept Comet Giacobini-Zinner) provided a valuable data set from a well-instrumented spacecraft. Other reasons for interest are intrinsic to the nature of the solar wind interaction at these distances downstream. Here the Mach number of the bow shock can become quite low, enabling us to investigate the transition from subcritical to supercritical shock fronts. We are also far from the leading edge of the foreshock, which allows us to observe the evolution of foreshock turbulence and attempt to distinguish upstream effects from phenomena that are integral with the shock structure. The geometry of this region is also different from that of the well-studied subsolar bow shock. On the dayside, the shock normal is nearly coaligned with the solar wind velocity, while on the flanks these two vectors are nearly orthogonal. This produces a second degree of freedom in the upstream shock parameters and also influences the trajectory of reflected particles parallel to the
shock surface. The low Mach number regime is also important because of the wealth of numerical simulations that have been performed in this parameter range and we have made use of these results for comparison with our spacecraft observations.

In the following sections we present our results organized by region: foreshock, shock and magnetosheath. Our studies have also supplemented related studies of shock physics in other areas (i.e. the solar corona) and we will also discuss these secondary contributions.

Foreshock

The extensive foreshock upstream of the Earth’s bow shock, replete with turbulent plasma wave emissions, ULF magnetic field turbulence, and back-streaming particles, has been the subject of much study both to understand its intrinsic properties and to understand its relationship to the bow shock. In the subsolar region of the shock, for quasiparallel geometries, the foreshock and shock structures are intertwined as particles stream away from the shock and create foreshock turbulence which is blown back into the shock. On the far flanks we have a chance to try and view these effects decoupled, as the shock and foreshock leading edge are now far apart. We are also detecting shocks at Mach numbers near the limit where ion reflection begins to alter the magnetic field structure of the shock ramp. While the fluxes of reflected ions may be too small to produce noticeable magnetic field turbulence, they still have the potential to generate plasma waves. However, a new difficulty arises from the geometry of the far flanks, where the shock normal is now nearly orthogonal to the solar wind flow instead of coaligned.

As this research effort was getting underway, Greenstadt et al. [1991] presented an initial overview of the flank shock data set and compared the magnetic field profiles of several shocks with those found in weak, quasiparallel numerical shock simulations. These examples showed that even at low shock normal angles ($\theta_{Bn}$) there was an absence of significant ULF turbulence upstream. However, there was often a pronounced whistler-like wavetrain either immediately upstream or downstream of the shock ramp. The simulations indicated that wavetrains only occurred when the Alfven Mach number ($M_A$) exceeds 2.5, and this effect was corroborated in the flank shock data set. Clearly, this whistler-like wavetrain is a structure produced by the shock itself, while ISEE 3 was apparently too far downstream of the foreshock leading edge to detect strong ULF turbulence produced by foreshock particle populations. The nearly laminar appearance of
the quasiparallel flank shocks illustrated quite a contrast with the broad, turbulent quasiparallel shocks of the subsolar region.

Greenstadt et al. [1992a] set out to investigate in more detail the controlling factors in producing upstream particles by using broadband plasma wave emissions as a diagnostic of their presence. They found that these low Mach number shocks still produced copious amounts of plasma emissions upstream, but that the controlling factors were modified due to the unusual shock geometry on the flanks. A new parameter was introduced to aid in organizing the data—the angle between the IMF and the solar wind velocity ($\theta_{Bx}$ in GSE coordinates). In the subsolar region $\theta_{Bx}$ and $\theta_{Bn}$ are nearly equal, but they vary independently on the flanks. For decreasing values of $\theta_{Bx}$ it was found that the extent of upstream plasma wave turbulence increased. Greenstadt et al. [1992a] concluded that this was caused by particles reflected upstream of the spacecraft location convecting back along the IMF with trajectories nearly parallel to the shock surface. Thus, nonlocal effects were shown to be important in the plasma waves, although not in the magnetic field, and upstream and reflected ion populations were still present without the ULF turbulence characteristic of the subsolar foreshock.

Greenstadt et al. [1992b] attempted to further define the contributions of $\theta_{Bx}$ and $\theta_{Bn}$ to the presence of upstream plasma wave turbulence by developing a scatter diagram showing the presence or absence of upstream waves. This ran into difficulties in distinguishing "foreshock" waves from "shock foot" waves. Subsequent analyses searched for additional parameters to aid in making this distinction, but adequate results were not forthcoming. A discussion of the work on employing plasma waves in detecting the presence of a shock foot appears in the next section.

ISEE 3 plasma wave data was also used to obtain a global view of the foreshock using a wave amplitude mapping scheme devised for Venus [Crawford et al., 1993]. In this scheme, the wave amplitude in a particular channel is plotted as a function of its position in foreshock coordinates [Greenstadt and Baum, 1986] (distance along and depth behind the foreshock leading edge) to create a relief map of the wave activity independent of the orientation of the IMF. Greenstadt et al. [1993] presented a preliminary example of the results using one ISEE 3 trajectory through the foreshock and wave amplitudes corresponding to the electron plasma frequency ($f_{pe}$) and compared the resulting map with a similar one for Venus. At this stage the sampling spatial scale for Earth was still crude, since this employed data from only one Earth pass, while the Venus map was based on
thousands of PVO orbits. Yet, the terrestrial map showed the much greater scale of the Earth's foreshock compared with Venus and clearly delineated the enhanced wave activity in a thin band corresponding to the foreshock leading edge. This band of activity also had a definite termination near 100 Earth radii from the shock tangent point. Further analysis, unfinished at the time of this writing, will include a second ISEE 3 foreshock traversal. Line plots of intensity percentiles from both passes show pronounced maxima in median and higher intensities of wave peaks at, and just downwind from, the tangent IMF surface to the shock, much as in the Venus foreshock. It is hoped that this approach will be extended to include lower frequency waves associated with reflected ions. The foreshock defined by the low frequency plasma waves can then be compared with that defined by ULF structure in the magnetic field.

Shock

Greenstadt et al. [1992a] also addressed the problem of supercriticality in low Mach number shocks. The critical Mach number occurs when the shock can no longer create enough resistive dissipation, and must reflect a portion of the incoming ion flow. Theoretically this Mach number is defined as the point when the downstream flow speed exceeds the downstream acoustic speed as computed by the Rankine-Hugoniot relations. The usual way of identifying supercritical shocks is by the presence of a downstream "overshoot" and/or a "foot" to the shock ramp in the magnetic field profile. Some recent research has looked into the transition from sub- to supercritical shocks by searching for low fluxes of reflected ions in closed trajectories upstream of low Mach number shocks. The problem is naturally the ability to detect ion beams at low densities, but results indicate that the transition is not sudden and some reflected particles can be found even at the lowest Mach numbers.

Plasma waves can be even more sensitive to superthermal particle populations than direct particle detection, since they give rise to instabilities that cause the rapid growth of waves to detectable amplitudes. Greenstadt et al. [1992a] used the ISEE 3 flank shock data set as a source of low Mach number shock profiles and searched for a plasma wave foot immediately upstream of the shock ramp. It was found that most of the shocks were actually supercritical using the theoretical criterion given above, but one example was subcritical according to the Rankine-Hugoniot relations and many did not evidence a foot in the magnetic field profile. This ostensibly subcritical shock had a substantial plasma wave foot, showing that ion reflection was still taking place.
A more detailed study of the waves at and immediately downstream from the flank bow shocks was conducted by Coroniti et al. [1993]. The wave amplitudes at even the weakest shocks were found to be comparable with those found at high Mach number subsolar shocks. When examined at the highest time resolution, the plasma wave spectra revealed two modes in the mid-frequency band usually assigned to ion acoustic waves. Previous observations, concentrating on lower time resolution data or limited parts of the spectral band, identified only a single mode extending from approximately the electron cyclotron frequency ($f_{ce}$) to nearly the electron plasma frequency. The ISEE 3 results clearly show two modes with different temporal characteristics and quite independent of one another (the appearance of one mode is neither correlated or anti-correlated with the other).

The higher frequency mode is usually found between $1.0 - 0.1 f_{pe}$, and is distinguishable from narrowband electron plasma oscillations by its much broader bandwidth. These waves are found at frequencies above that expected for electrostatic waves Doppler-shifted by the solar wind and are outwardly similar to so-called "down-shifted" electron plasma oscillations detected deep within the foreshock [Fuselier et al., 1985]. These emissions are strongly polarized parallel to the magnetic field. Coroniti et al. [1993] suggests that the instability generating these waves could arise from discontinuities in the electron distribution function. Such discontinuities would be the result of contact along the field lines between electron populations with different thermal characteristics. As electron populations encounter the cross-shock electric field, a void develops in the low energy region of the distribution function, which must be filled by scattering. With insufficient time to be relaxed through thermalization, the discontinuity in the electron distribution will produce an instability that can create waves at frequencies of a few tenths of the plasma frequency.

More of a mystery is the lower frequency emission, which occurs with a peak near the ion plasma frequency ($f_{pi}$) between 100 and 300 Hz. This mode is often separated from the higher frequency component by a pronounced spectral gap. Time series data shows that this emission is extremely bursty with peak to valley ratios of 100 to 1000 occurring in succeeding time samplings, unlike the smoother time profile of the high frequency emissions which only display a spin-modulated ripple of less than an order of magnitude. The burstiness of this emission renders polarization determinations difficult, but a slight parallel polarization can sometimes be discerned. It is also impossible to distinguish any
festooning effect caused by the response of the antennas to waves with wavelengths comparable to the antenna length [Gallagher, 1985]. What causes these waves is still not known. We do not observe any apparent frequency control by Doppler-shifting, although the absence of wideband data on ISEE 3 makes detailed spectral analysis difficult. The lack of any influence in the wave frequency by the value of the electron cyclotron frequency, which often occurs in this band, suggests an instability with $k$ parallel to $B$. A parallel instability would more likely arise from variations in the electron distribution, but participation by the ions cannot be disregarded.

**Magnetosheath**

When observed from a global perspective, the magnetosheath has also been found to have new and interesting properties. Moses et al., [1992a] presented long time series data showing several days of the ISEE 3 pass through the magnetosheath and foreshock. The sheath can be distinguished by the brightness of the broadband emissions there compared with the foreshock, even in the quasiparallel region. The sheath also contains electron plasma oscillations virtually throughout its extent toward the boundary with the tail lobe over 150 $R_E$ downstream. This is quite surprising, since electron plasma oscillations are commonly considered a foreshock phenomenon.

The cause and nature of the broadband emissions far downstream of the bow shock are as yet unknown. Ion acoustic instabilities have been frequently invoked, but the difficulty of generating these emissions with the known ion temperatures has not been satisfactorily overcome. More needs to be learned about these emissions, and we have found a new factor controlling the emissions that could be fundamentally important in understanding their nature. A preliminary study [Moses et al., 1993] and detailed follow-up [Coroniti et al., 1994b] show that the direction of the magnetic field can have a significant effect on the presence or absence of wave emissions throughout the magnetosheath. Occasionally we noticed flank shocks without any waves at all immediately downstream and such dropouts were also observed much further inside the magnetosheath. During these times the wave amplitudes are reduced nearly to the instrument background. Surprisingly, these dropouts correspond to times when the component of the magnetic field parallel to the solar wind flow velocity (roughly the $x$-axis in GSE coordinates) goes to zero. No other factor seems to control the waves and the dropout effect occurs for any orientation of the magnetic field in the plane perpendicular to the flow. Occasionally a decrease in $B_x$ also corresponds to a decrease in $|B|$, but this is not a prerequisite for a plasma wave dropout.
One reasonable explanation for this effect would be Doppler-shifting of low-frequency, parallel-polarized modes. The search for evidence of Doppler-shifting proved negative, however, as the peak frequency of the waves did not shift with intermediate values of the angle between the magnetic field and \( x (\theta_{B_x}) \). The overall amplitudes do decrease in any given channel with intermediate values of \( \theta_{B_x} \) suggesting that this parameter must influence the instability directly. We also do not observe an increase in amplitude with decreasing frequency, that would be indicative of Doppler-shifting.

The only hypothesis that seems consistent is that the direction of the magnetic field is controlling the nature of the connection of the field lines to the shock or magnetopause. This would determine the characteristics of the counter streaming electron populations that form the downstream distribution. When \( \theta_{B_x} \) is 90° the shocks at either end of the field line are most likely to have similar properties (Mach number and shock normal angle), while other values of \( \theta_{B_x} \) will lead to connection to shocks with differing characteristics. It is reasonable to assume that the symmetric case will lead to electron populations counterstreaming with nearly symmetric distributions, thus avoiding any discontinuities in the distribution function that would cause an instability. Connection to the magnetopause does not seem to be a factor, since this would only occur for large values of \( B_y \). Although sketchy, this scenario is the only one that fits the phenomenology; however, its verification depends on detailed measurements of the electron distribution at low energies, which are difficult to obtain.

Related Studies

One of the original motivations at TRW to study the flank bow shock crossings was to apply the results to the ISEE 3/ICE encounter with Comet Giacobini-Zinner. *Smith et al.* [1986] used the Rankine-Hugoniot relations to argue that the crossings of the solar wind interaction regions of Giacobini-Zinner were low Mach number shocks, which was consistent with the arguments of *Scarff et al.* [1986] and *Kennel et al.* [1986] that the plasma wave phenomenology was indicative of shock crossings. These analyses were based on examinations of data on long timescales and other studies questioned the existence of an actual shock at Giacobini-Zinner. *Moses et al.* [1992] set out to examine the plasma wave data at the highest possible resolution (0.5 s) and compare the wave emissions with those found at weak flank shocks. At this resolution, it was hoped to be
able to associate various wave activity with ULF magnetic field turbulence which dominates the structure of the interaction region. No strong correlations between magnetic field structures and plasma wave spectra could be found, although the wave spectra tended to become more complicated (multi-peaked) as the magnetic field turbulence became more nonlinear. The high resolution analysis did show, however, that the same division between high frequency and low frequency emissions found in the flank shocks was evident in the comet waves. Moses et al. [1992] argued that the similarity in wave spectra probably arises from a similarity in microphysical processes in both cases. Thus the wave generation mechanisms at the comet are produced by the deceleration and compression of the solar wind associated with the ULF pulses (analogous to the processes in the ramp of a weak shock) and not by instabilities dependent directly on picked-up heavy ions.

In Moses et al. [1991] we applied some of the results from our low Mach number shock studies to conditions that could be encountered by a spacecraft penetrating the solar corona. Studies have been performed of missions designed to achieve heliocentric distances of 4 solar radii. At these distances magnetohydrodynamic models predict that the steady state solar wind is subsonic. But dynamic simulations show that low Mach number shocks could develop under extreme conditions. The closest analogy to such shocks in the corona would be quasiparallel bow shock crossings on the far flanks. We had earlier illustrated that even the lowest Mach number shocks on the flanks could produce magnetic field turbulence with $\delta B/B$ of order 1 and copious emissions of broadband plasma waves. Solar corona shocks would be in the slow mode (sub-Alfvenic) for $\beta << 1$ and not likely to produce large magnetic oscillations, but on the far flanks large amplitude turbulence was found even for $\beta = 0.4$. We therefore concluded that the solar corona could be expected to be extremely turbulent, with Doppler shifting caused by high spacecraft speeds to result in magnetic oscillation amplitudes of order Gauss at frequencies over 100 Hz. Again, using scaling arguments based on far flank shocks, we predicted electric field oscillations could attain amplitudes of order volts/meter at frequencies near 100 kHz. Such strong turbulence will also drive the plasma up to the Alfven speed and produce nonthermal motions up to 200 km/s, which is near to the velocity fluctuations that have been deduced from radio scintillation and Lyman $\alpha$ measurements. To measure such wave activity would require specially designed instrumentation, with dynamic ranges and sensitivities drastically different from those previously flown.
Remarkably similar phenomenology to the flanks shocks was also found in slow mode shocks on the boundaries of the plasma sheet in the distant magnetic tail [Moses et al., 1992b; Coroniti et al., 1994a]. As in the fast mode flank shocks, the broadband emissions in the slow mode shocks were found to be made up of two independent wave modes. The higher frequency mode also showed a strong parallel-polarization and exhibited a time profile modulated by a low amplitude spin-ripple. The low frequency modes were much burstier, with peak-to-valley ratios of 100 to 1000, and only a slight tendency toward parallel polarization. It thus appears that we are observing similar microphysical processes in distinctly different regions. Both the fast shocks and slow shocks have density compressions and the electron distributions in the parallel directions are controlled by the cross-shock electric field, but the magnetic field jumps, which should control the change in the perpendicular components of the distributions, are in opposite directions. This again points strongly to instabilities arising from free energy in the parallel component of the distribution.

Conclusions

The study of the solar wind interaction region on the far flanks has proven quite fruitful and has added to the understanding of processes in the foreshock, shock, and magnetosheath. We have discovered new wave modes and seen how different magnetic field geometries influence the presence and character of the waves. We have explored the important boundary between subcritical and supercritical shocks and mapped the global wave amplitudes in the foreshock. We have also applied the knowledge gained from the far flank shocks to the magnetotail, comets, and the solar corona. Much more can still be done both in exploring new phenomenologies and developing theories and models. This study, in a small way, shows the value of sustained research on existing data sets and the benefits of parallel investigations in related areas. Continued commitment to this mode of research, and support of well-established scientific teams, would have added to the advancement of scientific understanding in this field.

References


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Moses, S. L., E. W. Greenstadt, F. V. Coroniti, and E. J. Smith, Plasma wave activity in the deep magnetosheath inside the far flanks of Earth's bow shock, presented at the Spring Meeting of AGU, Montreal, Canada, May, 1992.*


*Papers supported under this contract

**Related research papers*
APPENDIX A
On the Absence of Plasma Wave Emissions and the Magnetic Field Orientation in the Distant Magnetosheath. (Preprint)
On the Absence of Plasma Wave Emissions and the Magnetic Field Orientation in the Distant Magnetosheath

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Abstract. In early September, 1983 ISEE-3 made a long traversal of the distant dawnside magnetosheath starting near \( x = -150 \) \( R_E \) downstream. The distant magnetosheath often contains moderately intense plasma wave emissions at frequencies from several hundred Hz to 5 kHz. However, over time scales of many days, a clear correlation exists between the occurrence of the plasma waves and the cone angle (\( \theta_{xB} \)) between the magnetic field and the plasma flow velocity (x-direction). For \( \theta_{xB} \) large (small), the plasma wave amplitudes are near background (high). Sudden (< 1 minute) changes in the local magnetic field orientation produce correspondingly sudden changes in the wave amplitudes. Statistically, the wave amplitudes decrease continuously with increasing \( \theta_{xB} \).

Introduction

Numerous observations from spacecraft have established that the Earth's bow shock excites a moderately intense band of plasma wave turbulence with frequencies between the ion and electron plasma frequencies (the so-called ion acoustic waves), which extends throughout the subsolar region of the magnetosheath [Rodriquez, 1978; Anderson et al., 1982; Onsager et al., 1989]. In September, 1983 the ISEE-3 spacecraft made a traversal of the distant dawnside magnetosheath starting about \( x = -150 \) \( R_E \) and moving eastward [Greenstadt et al., 1990] and detected many long intervals of wave excitation in the flank sheath similar to that in the subsolar sheath even at these large distances from the bow shock. In addition, however, the ISEE-3 plasma wave instrument also detected many abrupt dropouts in the plasma wave emissions between the tail magnetopause and the flank bow shock. We report here for the first time these striking and rather curious
absences of plasma waves and their correlation with the orientation of the magnetosheath magnetic field.

Observations

The ISEE-3 measurements by the TRW/U. of Iowa electric field wave detector [Scarf et al., 1978] and the JPL magnetometer [Frandsen et al., 1978] presented here were made from 0000 to 1200 UT on both September 10 and 12 (days 253 and 255), 1983. During these intervals the spacecraft was continuously in the magnetosheath moving from \( x = -158 \text{ RE} \), \( y = -28 \text{ RE} \) to \( x = -146 \text{ RE} \), \( y = -33 \text{ RE} \) (GSE). The \( x-y \) projection of the spacecraft's trajectory for this sheath pass is shown in Figure 1. On September 10 (12), the magnetosheath flow speed varied from 500 to 600 km/s (400 to 500 km/s), the electron temperature was steady at \( 1.6 \times 10^5 \text{ K} \), and the plasma density was in the range of 4 to 5 cm\(^{-3}\) (measurements from the LANL plasma analyzer). Figure 2 presents the measurements for September 12, 1983. The top panels display the 60-second average magnetic field components and magnitude. The central color panel presents the peak electric field amplitude (volts/meter) in the frequency channels from 100 Hz to 31 kHz which occurred during successive 60-second intervals. The next panel shows the magnetic field cone angle (\( \theta_{xB} \)) - the angle between the \( x \)-axis (nominal magnetosheath flow direction) and the magnetic field. The bottom two panels display the magnetic field longitude (defined so that 0° to 90° (-90° to 0°) corresponds to \( B_x \) and \( B_y \) having the same (opposite) signs), and the magnetic latitude.

Throughout this twelve hour interval plasma waves were almost continuously excited in the frequency band between 178 Hz and 3.1 kHz with the strongest signals occurring between 1.0 and 3.1 kHz. In addition intermittent bursts of electron plasma oscillations are evident in the 17 kHz channel. However, there are definite intervals of a few minutes duration when the peak electric field amplitude is near the background level of the wave instrument; clear examples are near 0020 UT, 0440 UT, 0650 UT, 0900 UT, and 1155 UT. In the magnetosheath and solar wind, the average (over 60 s) electric field amplitude can be near background while the peak amplitude will remain high; thus, a zero peak amplitude indicates the virtual absence of plasma waves.

The disappearance of the 178 Hz to 3.1 kHz wave emissions occurs when the magnetic cone angle exceeds 60° and is typically above 75°. From the top panels in Figure 2, large cone angles correspond to intervals in which \( B_x \) is small, while \( B_y \) and \( B_z \) have varying and comparable values. In particular the magnetic field latitude did not exceed 45° to 60° during the wave dropouts; since the ISEE-3 electric field antenna is in the ecliptic plane, a parallel polarized electric field signal will not be detected if the magnetic latitude was near 90°. The first four and sixth
dropouts occurred during small to moderate depressions in the magnetic field strength; however for the fifth and seventh dropouts, the field magnitude was steady.

Figure 3 presents the magnetic field and plasma wave measurements for 0000 - 1200 UT on September 10, 1983. From 0000 UT to 0400 UT and again from 0800 UT to 1200 UT, the magnetic cone angle was often near 90° or rapidly varied between 60° and 90°. Plasma wave emissions between 178 Hz and 3.1 kHz are virtually absent during these intervals except for brief isolated bursts which occur when the cone angle drops below 60°. Between 0420 UT and 0450 UT, the cone angle decreased to about 40°, and fairly continuous wave emissions developed. From 0600 UT to 0800 UT, the cone angle remained below 45° and strong plasma wave signals were detected; the continuity of the wave emissions was broken at 0715 UT by a brief increase of the cone angle to 80°. For this twelve hour period intermittent electron plasma oscillations at 17 kHz were present during intervals of both high and low cone angles, and their occurrence did not exhibit any clear correlation with the magnetic field direction.

Figure 4 presents higher resolution measurements for the interval 0150 UT to 0230 UT on September 12, 1983; the magnetic field is averaged over 3 seconds, and the electric field spectral amplitude is unaveraged with a resolution of 0.5 s. At 0154 UT the wave amplitudes drop to background as $B_x$ decreases to approximately 1 nT and $\theta_{xB}$ increases above 60°. During the wave dropout, the field magnitude stays constant, $B_y$ changes sign, and a strong $B_z > 0$ results in a high field latitude (approximately 70°). The wave dropout developed simultaneously in the frequency channels from 316 Hz to 3.1 kHz, and there was no evidence that the wave amplitudes swept downward (upward) in frequency as $B_x$ decreased (increased). At 0200 UT, a sharp drop of $B_x$ to near zero ($\theta_{xB} = 75^\circ$), again at constant field strength, produced a rapid decrease in the wave amplitudes. The cone angle remained high ($\theta_{xB} = 75$ to 90°) and wave amplitudes remained low from 0200 to 0208 UT, except for brief low frequency wave burst and $\theta_{xB} < 60^\circ$ dip at 0202:30 UT. Between 0208 and 0211 UT, $\theta_{xB}$ varied in the range 60° to 75°, and weak low frequency waves were observed. Except for a short burst at 0212 UT, these emissions terminated as $B_x$ decreased to near zero at 0211 UT. From 0212 to 0220 UT, the field magnitude dropped to quite low values, $B_x$ remained near zero, and all wave amplitudes were at background. At 0220 UT, the field strength recovered, $B_x$ jumped to become the dominant field component, $\theta_{xB}$ decreased to 10°, and the 1.0 kHz to 3.1 kHz wave amplitudes started to increase. The wave amplitudes reached their previous (before 0154 UT) high levels after 0222 UT.

The temporal variations in the cone angle and plasma wave intensities on September 12, 1983 were sudden, radical changes from moderate to high $\theta_{xB}$ (Figure 2). Hence the question arises as to
whether the plasma wave amplitudes vary continuously with $\theta_{xB}$ or simply cut-off for angles above some threshold. Figure 5 presents a scatter plot of wave amplitude in the 1.78 kHz channel versus cone angle for the same time period shown in Figure 2 (the amplitudes indicate peak values in 1-minute intervals). The graph shows clear agreement with the general nature of the day's events, with most points at high intensity when $\theta_{xB}$ was usually below 40° and a much smaller number of points at low intensity, or instrument sensitivity limit, when $\theta_{xB}$ was less commonly above 50°. The apparent declining trend of intensity with angle, however, implies a continuous rather than "on/off" relationship between the two quantities for all angles. The wide scatter could be caused locally by several factors, such as the impulsive character of the plasma wave signals and the rapid fluctuations of the cone angle.

Discussion

The above examples have clearly demonstrated that in the distant dawnside magnetosheath the occurrence of plasma waves in the 316 Hz to 3.1 kHz band is associated with the local magnetic field direction. This relationship held for the entire dawnside pass shown in Figure 1. We have also observed the same anti-correlation between wave amplitude and high values of $\theta_{xB}$ in the duskside magnetosheath, but not in the upstream solar wind. The anti-correlation is so distinct that the first inclination is to seek an instrumental explanation. The ISEE-3 antenna is in the ecliptic plane, and thus electric fields which are perpendicular to the ecliptic are not measured. However, even if the waves were polarized exactly parallel to the magnetic field, which is not at all clear or even likely, the large cone angles, which imply $B_x$ was small, usually occurred when $B_y$ was quite finite so that the magnetic field latitude did not exceed 45° to 60°; therefore, the cosine reduction in the projected measured field amplitudes cannot explain the virtual disappearance of the wave emissions.

If the wave polarization is strongly field-aligned, another conceivable explanation involves the Doppler shift frequency $\omega_D = k \cdot v$, which would vary as $\cos \theta_{xB}$. If the observed frequencies are dominated by $\omega_D$, the reduction of $\cos \theta_{xB}$ would shift the peak spectral amplitude to lower frequencies; thus on the higher frequency, falling part of the spectrum, the amplitudes would decrease, and the waves would appear to drop-out. However, in examining the temporal behavior of the amplitudes in the various frequency channels during changes in $\theta_{xB}$ (as in Figure 4), the spectral peak does not shift to lower (higher) frequencies as $\theta_{xB}$ increases (decreases). Hence we conclude that the dropouts are not due to $\theta_{xB}$ variations in the Doppler shift frequency.
The absence of an instrumental or Doppler shift explanation leaves the possibility that the wave emissions are controlled by parameters not included in this report or by the global connection of the magnetic field to the bow shock and/or magnetosphere. Since ISEE-3 was within 20-30 RE of the tail magnetopause, the local magnetosheath field lines could be influenced by the location, shape, and/or reconnection state of the magnetotail. We have checked on whether the plasma wave dropouts and turnons depend on the signs of $B_y$ and $B_z$, which could indicate a sensitivity to reconnection-related magnetotail structure and $B_y$-twist of the tail's orientation, and found no obvious relation. Since dropouts occur when $B_y = 0$, the intersection of the field lines with the magnetotail is not essential to produce the amplitude decreases. Thus we conclude that the wave dropouts are not obviously produced by connection to the magnetosphere.

The wave dropouts can persist for many minutes to hours, which indicates that the large scale structure of the magnetic field, not the small scale or local wiggles, is responsible for the absence of wave emissions. When $\theta_{AB}$ is large, the nose region bow shock is in a quasiperpendicular configuration over most of the region sunward of the terminator. Thus most of the magnetosheath ions which flowed past the ISEE-3 spacecraft on September 10 and 12, 1983 crossed a quasiperpendicular shock, and thus might be expected to possess at least the remnants of a reflected ion or ring-type phase space distribution. Downstream of the terminator, the field lines would typically intersect the weak flank shock surface in the quasiparallel configuration. Since the magnetosheath electrons (ions) have thermal speeds of about 20 RE/min (0.5 RE/min) the local electrons (ions) would (not) have passed through a quasiparallel shock. Furthermore the shock strength at the two intersection points of the field line would be about equal, so that the distribution function of the shocked electrons would tend to be symmetric with respect to the parallel velocity. Thus the absence of plasma waves when $\theta_{AB}$ is large may be caused by the symmetry of the electron distribution in parallel velocity even if the local ion distribution contains remnants of the ring-type structure produced by ion reflection.

When $\theta_{AB}$ is small, the dawnside shock in the nose region is quasiparallel (quasiperpendicular) if the magnetic field is in a Parker (anti-Parker) spiral configuration. We found that the plasma wave emissions in the distant magnetosheath occur independently of the relative sign between $B_x$ and $B_y$; thus the waves are present for local magnetosheath ion distributions which have passed through either a quasiparallel or quasiperpendicular shock. For small $\theta_{AB}$, both the shock strengths and shock type at the two locations where the magnetic field line intersects the shock surface are very different. Thus the local electron distribution, which is in thermal contact with the bow shock, is likely to be asymmetric with respect to the parallel velocity.
In conclusion, one identified explanation we have been unable to eliminate for the observed anti-correlation of $\theta_{\times B}$ and plasma wave emissions is that when $\theta_{\times B}$ is small, the expected asymmetry in the local electron distribution leads to plasma wave excitation, and when $\theta_{\times B}$ is large, the field line connection to similar strength and type bow shocks results in a more symmetric electron distribution which is stable to wave emissions. Clearly GEOTAIL electron and ion plasma measurements will be able to test this possible explanation and/or provide a better one.

Acknowledgments

We acknowledge and pay homage to the late F. L. Scarf, the original Principal Investigator for the ISEE-3 plasma wave investigation, who made possible our participation in the study of plasma waves in space. The work at TRW was supported by NASA Contract NAS5-31216 with GSFC. The work at the California Institute of Technology, Jet Propulsion Laboratory was supported by contract with NASA.

References


Figure Captions

Figure 1. ISEE 3's magnetosheath trajectory for days 253-265, 1983. The heavy segments represent 10 and 12 September, when the spacecraft was approximately 17-18.5 RE above the x-y plane.

Figure 2. ISEE-3 measurements on 0000 UT to 1200 UT on September 12, 1983. The upper panels present the one-minute average components and magnitude of the magnetic field. The center panel is a color-coded display of the plasma wave electric field amplitudes (volts/m) from 100 Hz to 31.6 kHz. The bottom panels present the calculated magnetic field cone angle ($\theta _{B}$) and the longitude and latitude of the field as defined in the text. Clear dropouts in the plasma wave amplitudes occur when $\theta _{B}$ approaches 90°.

3. ISEE-3 measurements on 0000 UT to 1200 UT on September 10, 1983, in the same format as Figure 2. Plasma wave amplitudes are high only when the cone angle is below 40°.

Figure 4. High time resolution measurements from 0150 UT to 0230 UT on September 12, 1983. The bottom (top) panels display the measured (calculated) magnetic field components and magnitude (magnetic angles). The center panel shows the plasma wave spectral amplitude from 178 Hz to 3.16 kHz. Sudden changes in $\theta _{B}$ result in sudden changes in the wave amplitudes.

Figure 5. A scatter plot of the plasma wave electric field amplitude (volts/m) versus cone angle for the 0000 - 1200 UT interval on September 12, 1983. Although the scatter is large, the decrease of wave amplitudes with increasing cone angle is clear.
ISEE 3 September 12, 1983

B-field (nT)

E-field (Hz)

CONE

LON

LAT

0000 0400 0800 1200
APPENDIX B
Abstracts and First Pages of Publications
WEAK, QUASIPARALLEL PROFILES OF EARTH'S BOW SHOCK:
A COMPARISON BETWEEN NUMERICAL SIMULATIONS
AND ISEE 3 OBSERVATIONS ON THE FAR FLANK

E. W. Greenstadt1, F. V. Coroniti1, S. L. Moses1, B. T. Tsurutani2
N. Omidi3, K. B. Quest1, and D. Krauss-Varban2

Abstract. Over 200 crossings of the distant downwind flanks of Earth's magnetosonic bow shock by ISEE 3 included many cases of weak, or low Mach number, quasiparallel shocks. A consistent feature of the magnetic field profiles was the presence of large amplitude, near periodic to irregular transverse oscillations downstream from even the weakest Q1 shocks. Large downstream perturbations with whistler-like features similar to those of the observations appear in one-dimensional simulations when \( M_A > 2.5 \) but not when \( M_A = 2.1 \). The observed cases with downstream waves also occurred when \( M_A > 2.5 \), suggesting the importance of the Alfvén as opposed to magnetosonic Mach number in determining the signature of weak, Q1 shocks.

Introduction

We present observations of weak, quasiparallel bow shocks exhibiting large amplitude, downstream oscillations compatible with those of new numerical simulations of quasiparallel shocks that, although weak (low magnetosonic Mach numbers \( M_{Ma} \)), have moderate Alfvén Mach numbers \( (M_A) \) and downstream wavetrains. The terms quasiparallel \((Q_1)\) and quasiperpendicular \((Q_u)\) refer to planar shocks whose normal makes an angle \( \theta_{in} < 45^\circ \) or \( > 45^\circ \) from the upstream field \( B_j \). We use the term "weak," rather than "low Mach number," to describe the shocks of interest here. No local plasma ion data from which to approximate magnetosonic Mach numbers \( M_{Ma} \) were available from ISEE 3 at the time of the flank observations. Estimates of magnetosonic Mach numbers would have to assume a "typical" ion temperature, say \( T_i = T_e/2 \), and project the approximate solar wind ion velocities along the local normals. However, the upstream field magnitudes can be determined only when the spacecraft was outside the shock, so the instantaneous projected velocities, hence projected Mach numbers, especially for crossings that exit the magnetosheath, cannot be certain, and the speed of the shock itself, also necessary for determining its instantaneous Mach number, is unknown from ISEE 3's single-spacecraft crossing times. Instead of instantaneous Mach numbers, we have adopted the ratio of downstream to upstream field magnitudes \( M_B = B_j/B \) as a measure of shock strength approximating the true Mach number in \( Q_u \) but underestimating it in \( Q_1 \) geometry [Kennel et al., 1985]. In many of the over 200 flank crossings, \( M_B \) has been found to be the same or within one or two tenths of the projected \( M_{Ma} \), supporting the adoption of \( M_B \) as a practical tool for estimating shock strengths—without approxi-
POSSIBLE WAVE AMPLITUDES IN SHOCKS IN THE SOLAR CORONA:
PREDICTIONS FOR SOLAR PROBE
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Abstract. Shocks and Alfven turbulence are frequently invoked as mechanisms to heat the solar corona and accelerate the solar wind. A primary objective of the Solar Probe Mission is to detect and characterize these nonthermal dissipation and energization processes. Although the solar wind in the corona is usually assumed to be sub-Alfvenic, temporal and spatial variability in the plasma parameters could lead to conditions under which fast mode shocks might form. ISEE 3 data from the flanks of the Earth's bow shock show that even low Mach number, quasi-parallel shocks generate large-amplitude Alfven turbulence with dB/B of the order of 1, and intense high-frequency electrostatic plasma waves. Using a model of the corona and scaling parameters to those expected in the regions to be traversed by Solar Probe (r > 4 Rs), we suggest it is possible that such shocks might produce Alfven turbulence with magnetic field amplitudes up to the order of 0.1 G and electric field amplitudes up to the order of 1 V/m; electrostatic waves near 100 kHz may have amplitudes of 0.1 V/m. Since the shock-generated Alfven waves would be Doppler shifted to frequencies of a few kilohertz because of the high spacecraft velocity at perihelion, detection of these waves imposes severe requirements on the designs of plasma wave and magnetic field sensors on Solar Probe.

1. Introduction

Determination of the physical processes which heat the solar corona and accelerate the solar wind is a major objective for the planned Solar Probe Mission. Many of the proposed coronal heating and acceleration mechanisms involve interactions with magnetohydrodynamic (MHD) waves and shocks (a thorough review is given by Narain and Ulmschneider [1990]). Very low frequency Alfven waves may be generated by the 5-min photospheric oscillations and/or convection turbulence [Hollweg, 1983]. Coronal shocks can be excited by impulsive mass flows, diverging flow geometries, and/or local momentum addition [Habbal and Tsinganos, 1983]; such shocks are expected to have low Alfven Mach numbers and to be in the quasi-parallel regime. These theories are supported by observational evidence of turbulence in the solar corona. Withbroe et al. [1985] analyzed Lyman emissions in the region 2.8-4 Rs and found evidence for nonthermal motions with velocities 0.5-90 km/s. Radio scintillation measurements indicate a peak in the coronal random motions of v = 200 km/s near 10 Rs [Ekers and Little, 1971; Coles et al., 1978].

Within 10 Rs the solar wind in the corona is normally assumed to be sub-Alfvenic and low B. Therefore standing weak shocks should be on the slow mode branch and are unlikely to produce much hydrodynamic wave turbulence. Propagating fast mode shocks could be driven by rapid changes in the configuration of the lower corona, and these shocks could exceed the critical switch-on Alfven Mach number, above which shocks are expected to excite large-amplitude Alfven turbulence. In any case, much is still not known about coronal plasma parameters, particularly on small scales, and it may be reasonable to expect that local temporal and spatial variations may produce weak, fast shocks. However, the primary purpose of this paper is neither to debate the existence nor to explore the physical consequences of weak, fast shocks in the solar corona, but to point out that in attempting to measure the properties of such shocks, the Solar Probe instrumentation will be severely tested. At Earth, low Mach number, quasi-parallel shocks generate large-amplitude, high-frequency Alfven turbulence and intensive plasma wave emissions, and we suggest that similar shocks might produce extended regions of large-amplitude Alfven and plasma wave turbulence in the solar corona. In this paper we scale the terrestrial shock measurements to coronal parameters, and we argue that in order to properly characterize such phenomena, significant improvements on current instrument designs will be necessary for Solar Probe.

In section 2 we present one particular model of coronal shock formation to obtain an estimate of likely shock parameters. Section 3 presents cases from the ISEE 3 crossings of the far flanks of the Earth's bow shock that fit these parameters and discusses the character of the wave activity found downstream. In section 4 we scale the turbulence in the magnetosheath to predict the amplitudes and frequencies of wave emissions in the regions to be encountered by Solar Probe. In section 5 we discuss the impact of these results on the scientific requirements of the Solar Probe mission, and this is followed by a brief summary.

2. Coronal Shocks

Kopp and Holzer [1976] showed that additional critical points can appear near the base of the corona when the rate of divergence of flux tube area with increasing radial distance is greater than r^2; Holzer [1977] extended this result by showing that additional points could also be obtained by localized heat and momentum addition to the flow. For flows with multiple critical points, Habbal and Tsinganos [1983] proposed that shocks could develop in the solar wind flow; later Habbal and Rosner [1984] and Habbal [1985] found solutions involving standing shocks in the near-Sun solar wind flow. Recently Leer and Holzer [1990] have argued that standing shocks are extremely unlikely for the plasma parameters expected in coronal holes. However, smaller-scale structural variability in either the magnetic field configurations or the plasma parameters might produce shocks, which need not stand in the solar wind flow but propagate in the corona.

Figure 1 presents some results from hydrodynamic simulations of the solar corona contained in Figure 3 of Habbal and Rosner [1984]. Each of the panels in Figure 1 depicts the density profile of the solar wind within 6 Rs. The top panel shows the steady state configuration which develops when momentum is applied to the flow gradually (rise time of 2 x 10^4 s) and creates a standing shock. The magnitude of the density jump of this shock, n_2/n_1, is approximately 2. The middle panel shows a

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0148-0227/91/91JA-02265S02.00
StrucuClure are correlated with the downstream distance from the magnetle field instrument.

S J BORon

Also the bulk motion of the shock is known to evolve in the presence of background density fluctuations that disrupt the wave packet. The following conclusions are reached following the published data and instrument analysis:

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During Voyager 2's approach to Neptune, the spacecraft measured a high Mach number (M = 36) and high β (β = 6) bow shock. Preliminary calculations (Stasbo et al., A.G.U. Abstracts Spring 1995 Meiring) suggested an event of a pedestal shock normal to the local interplanetary magnetic field (IMF). Using the non-linear least squares technique of Epstein and Scudder (J. Geophys. Res. 92, 39, (1987)), we determined that the angle between the bow shock normal and the IMF is 55°, with a 15° uncertainty. The motion of the bow shock was determined to be 15 + 10 km/s moving away from the planet, towards the Sun. With the knowledge of the bulk speed of the shock, the scale length of the front and the shape of the shock, we can calculate the theoretical results expected for this event.

R P. Lepping (NASA Goddard Space Flight Center, Code 692, Greenbelt, MD 20771)

The distance of the bow shock from a planetary obstacle is determined by the compressibility of the plasma and the Mach number of the flow. As the bow shock is the only weakly compressed and the shock must move away from the planet in order to accelerate all of the knocked down particles to move away from the planet. Also, we have compared Voyager Venus data at times when the interplanetary magnetic field is strong and at a lower magnetic Mach number, respectively. Our observations indicate that it is not possible to extend these simulations, particularly MHD simulations to lower Mach numbers. Also, these mathematical simulations of interplanetary shock locations are not representative of planetary magnetic fields when the Mach number of the shock is unknown.

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Plasma Wave Profiles of Earth's Bow Shock at Low Mach Numbers: ISEE 3 Observations on the Far Flank

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The Earth's bow shock is weak along its distant flanks where the projected component of solar wind velocity normal to the hyperboloidal surface is only a fraction of the total free stream velocity, severely reducing the local Mach number. We present a survey of selected crossings far downstream from the subsolar shock, delineating the overall plasma wave (pw) behavior of a selected set of nearly perpendicular crossings and another set of limited Mach number but broad geometry; we include their immediate upstream regions. The result is a generalizable pw signature, or signatures, of low Mach number shocks and some likely implications of those signatures for the weak shock's plasma physical processes on the flank. We find the data consistent with the presence of ion beam interactions producing noise ahead of the shock in the ion acoustic frequency range. One subcritical case was found whose pw noise was presumably related to a reflected ion population just as in stronger events. The presence or absence, and the amplitudes, of pw activity are explainable by the presence or absence of a population of upstream ions controlled by the component of interplanetary magnetic field normal to the solar wind flow.

INTRODUCTION

The collisionless, high $p(\sim 1)$ shock in a magnetized plasma is in general a complicated phenomenon, but it should appear in its simplest manifestations when the Mach number is low. At its weakest, the shock has been assumed for years to display a smooth steplike jump or a dispersive wave profile, with modest jumps of magnetic field and density unlikely to disrupt the laminar flow of plasma from upstream to downstream states, while bestowing on it a mild temperature increase [Auer et al., 1971; Mellott, 1985]. Relatively clean profiles of low-M shocks were in fact obtained analytically and experimentally two decades ago, but cases were necessarily simplified to achieve both analytic solutions and reproducible laboratory results [Tidman and Krall, 1971; Robson, 1969].

Satellite measurements in space plasmas offered the first opportunities to observe nature's solutions to the collisionless shock problem and to test the validity of theory- and laboratory-bound simplifications, but low-M shocks have turned out to be relatively scarce in the accessible extraterrestrial environment where most missions have gone. The Earth's bow shock is commonly strong ($M > 5$) in its subsolar region, where the great bulk of natural shock observations have been made, although solar wind variability has occasionally produced low-M conditions. Interplanetary shocks launched by solar activity or coronal inhomogeneities are often weak ($M \sim 2$), but they are encountered unsystematically and pass deep space probes too fast to reveal their structures to any but the fastest instruments and sampling systems. Nevertheless, interest in, and the importance of documenting, weak shocks has motivated investigators to collect and examine the available events, with somewhat surprising results: The presumably simplest (or borderline simplest) of shock displays have included nonlaminar cases with unexpected heating [Thomson et al., 1985] and unanticipated magnetic and plasma wave profiles compatible with the presence upstream of small numbers of reflected ions not always detectable by particle instruments [Greenstadt and Mellott, 1987; Mellott and Greenstadt, 1988].

The chief indirect evidence for reflected ions has been the occurrence of elevated plasma wave (pw) signals between 10 Hz and 3 kHz, in the range of lower hybrid and ion acoustic frequencies in the otherwise undisturbed interplanetary magnetic field (IMF) immediately outside of low-M shock ramps. The signals are attributable to ion beam instability and are detectable because of the relatively high sensitivity of pw detectors to waves produced by even low densities of counter-streaming protons. The number of cases on which the pw evidence has been based has been small, however, but study has recently begun on a massive collection of weak shock observations made by ISEE 3 during its repeated crossing of the downwind bow shock in 1982 and 1983. The collection contains mostly low-M shocks because much of the satellite's time was spent where the weakened bow shock approaches its asymptotic Mach cone far downwind from Earth [Greenstadt et al., 1990]. The purpose of this report is to confirm and enlarge the earlier results with a more comprehensive, although still preliminary survey of cases covering a range of local Mach numbers and IMF orientations, from quasi-perpendicular ($Q_\parallel$) to quasi-parallel ($Q_\parallel$).

The sections immediately following describe our form of data presentation, scheme of case selection, and method of defining shock strength and then present our examples and discuss our interpretation of them.

DATA PRESENTATION

Shock Subsets

The pool of 110 shock crossings described by Greenstadt et al. [1990] has been augmented, with the help of J. T. Gosling...
M. Pekarek (HEDC, St. Petersburg State University, RUSSIA, and University of Iowa, USA) and A. V. Romanova (Institute of Geophysics, Academy of Sciences, RUSSIA)

A new family of Tyaganenko 87 models incorporating plasma sheet warping effects, and organized according to Solar Wind (SW) and Interplanetary Magnetic Field (IMF) parameters, has been derived. The new models are based on the recently expanded (EXPAND) magnetic field database used to construct the original 87 model (T. J. Philbrick, private communication). The EXPAND database used to construct the orbit 87 model has been corrected for offsets and distortions, and the resulting response to SW and IMF variations compared to the original Tyaganenko models. Our results show that the new models better describe the solar wind space environment. The new model was found to be more accurate in predicting the plasma sheet warping effects.

A two-dimensional (2-D) model of the plasma sheet is presented, which takes into account the warping of the plasma sheet in response to the solar wind. The model is based on the extraction of key parameters from the original 87 model and the EXPAND database. The model is validated using data from the ISEE-3 spacecraft, and it is found to be in good agreement with the observed plasma sheet warping effects. The model is shown to be more accurate in predicting the plasma sheet warping effects than the original 87 model.

The development of the cross-field current instability is investigated for conditions for the Earth's neutral sheet just prior to current disruption. Numerical solution of the quasi-linear kinetic equations shows the wave growth rate remaining the same at least for less than one ion gyroperiod. The ion drift speed is found to be reduced by ~15-25% of its initial value, accompanied by non-adiabatic heating of the plasma. It is also shown that the plasma in the instability region is subjected to a substantial net force in the direction perpendicular to the wave for certain amount of current due to the instability growth.

We observed that the plasma sheet is divided into two generally different plasma populations. The two populations differ in their temperatures and pressures. The plasma sheet is divided into two generally different plasma populations. The two populations differ in their temperatures and pressures.

The double-peak current density distribution in the plasma sheet is found to be two generally different plasma populations. The two populations differ in their temperatures and pressures. This double-peak distribution is found to be characterized by two peaks, one near the Earth and the other further out in the plasma sheet. The double-peak distribution is found to be characterized by two peaks, one near the Earth and the other further out in the plasma sheet.

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Observations of Plasma Waves in the Solar Wind Interaction Region of Comet Giacobini-Zinner at High Time Resolution

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B. T. Tsurutani

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High-time-resolution spectra of plasma wave emissions detected in the interaction region of comet Giacobini-Zinner with the solar wind reveal a wave phenomenology much more complicated than first reported. Spectra often exhibit three or more independent peaks, which become more prominent the deeper into the interaction region the spacecraft traversed. The main peaks correspond to whistler emissions below the electron cyclotron frequency, a midfrequency peak near the maximum Doppler shift frequency for waves with \( k_A P = 1 \), a high-frequency peak above the Doppler shift maximum frequency, and electron plasma oscillations at the plasma frequency. Similar multi-peaked spectra are also observed downstream from weak shocks at Earth, which suggests that the plasma wave generation mechanisms responsible need not require particle populations created by photionization.

INTRODUCTION

One of the most prominent issues to arise after the encounter of the International Cometary Explorer (ICE) with comet Giacobini-Zinner on September 11, 1985, is whether the interaction of the solar wind with the heavy ions produced near the comet creates a bow shock around the comet. Measurements made by the ICE plasma wave detector (PWS) were among the data used to support the existence of a shock [Scarf et al., 1986; Kennel et al., 1986], and an analysis utilizing the Rankine-Hugoniot relations suggested that a low Mach number shock was crossed both inbound and outbound [Smith et al., 1986]. These studies employed long time-scale averages of the data to obtain a global picture of the comet encounter. In contrast, using numerical simulations of the ion pickup region, Omidi and Winske [1988] argued that the solar wind did not encounter a single shock but was slowed by the cumulative effect of steepened magnetosonic waves, known as "shocklets", which increase in number and amplitude nearer the comet. This model is consistent with the signature of steepened magnetosonic waves in the magnetic field deep inside the interaction region [Tsurutani and Smith, 1986], the absence of a single identifiable shock transition, and electron plasma data in which shock-heated downstream plasma was interspersed with seemingly unshocked solar wind [Thomsen et al., 1986]. However, it has not yet been shown that the steepened magnetosonic waves in the comet are causing the deceleration of the solar wind.

Similar magnetic field and plasma wave conditions were found at comet Halley during the encounters by the Giotto and VEGA spacecraft, and Tsurutani [1991] presents a detailed review of the phenomenology found at both comets. The magnetosonic waves detected upstream of Halley were reported to be of smaller amplitude, but more turbulent appearance, than those found at Giacobini-Zinner [Johnstone et al., 1986] and it has been suggested that this might be due to the greater distances over which waves were generated at Halley, which would allow more wave-wave interactions to occur. In general, the clean progression in the development of steepened magnetosonic waves observed at Giacobini-Zinner was not seen at Halley. Intense plasma wave activity was also observed at Halley, although the sensitivity of the plasma wave detectors flown on those spacecraft was at least an order of magnitude poorer than for the ICE PWS (this is due to the extremely long length, 90 m tip to tip, of the ICE electric field antennas).

The purpose of this paper is to present the plasma wave observations made at Giacobini-Zinner on a time scale that resolves individual steepened magnetosonic waves and compare them with similar high-resolution observations of weak terrestrial bow shocks. On this scale the wave spectra at the comet are highly variable and reveal more wave modes than previously assumed, but similarities can still be found between the cometary spectra and those from weak shocks at Earth. In the next section we will illustrate the evolution of the wave spectrum as the magnetosonic waves steepen and describe the different wave modes. The third section presents the plasma wave data from weak quasi-parallel shocks observed on the flanks of the Earth's bow shock and contrasts them with the comet examples. The fourth section contains a discussion of the results in the light of previous wave generation models. This is followed by a brief summary.

GIACOBINI-ZINNER OBSERVATIONS

Figure 1 shows the magnetic field data for the 1-hour interval containing the inbound shock crossing (top panel) and 5-min-averaged electric field spectra which illustrate the shocklike characteristics of the plasma waves as used by Kennel et al. [1986] in the initial report on plasma waves in the solar wind interaction region. The upstream region was found to contain electron plasma oscillations at the plasma frequency, \( f_p \), and broadband emissions with frequencies from about 100 Hz to nearly 10 kHz. These signals are similar to waves observed in the ion foreshock at Earth and are often called (for lack of a
1993 Fall Meeting
Page 515

SM22B
CA: 415
Tues 1330h
Magnetic Reconnection: Onset of Magnetopsheric Substorms and Solar Eruptive Processes II (joint with SH)
Presiding: B Sonnerup, Dartmouth College

$\text{SM22-1}$
1330h
POSTER
Observational Aspects of Magnetic Reconnection at Earth's Magnetopause
L T. Godt
Los Alamos National Laboratory, Los Alamos, NM 87545; 505-667-5353; jmgodt@lanl.gov

Measurements made in the vicinity of the magnetopause have provided a direct demonstration that reconnection between the interplanetary magnetic field (IMF) and the interplanetary plasma sheet occurs at the magnetopause. These measurements tell us much about where and when reconnection occurs as well as the nature of the reconnection flow lines at the magnetopause, but tell us very little about details of the processes involved in this so-called "diffusion region". Direct evidence for reconnection is best provided by observations of bulk plasma accelerations and plasma refraction and transmissions that occur in the plasma ion and electron regions of the low latitude boundary layer (LBL), and in systematic oscillations in the normal magnetic field component popularly known as flux transfer events. Interestingly, a signature of reconnection does not appear to lead directly to either substantial plasma heating (although some occur) or substantial particle acceleration and transport in the outflow region. We argue that the dominance of either the mirror or ion cyclotron instabilities is most apparent in the transport processes. We compare the occurrence of different wave types with instability criteria derived from both MHD and kinetic theory. We also report on a study of the effects of these instabilities on the ion distribution functions.

$\text{SM22-2}$
1330h
POSTER
Effects on Thermal Ions, He+, Ne+ and O+ Associated with Ion Cyclotron Waves
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AMPTLE-ANDERSON
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Electromagnetic ion cyclotron waves are widely thought to interact with ion beams heavier than protons and some evidence has shown heating effects and phase bunching of ions. Increased ion densities have also been attributed a causative role in enhancing amplification of waves with magnetic and electric field components. We examine waves at H+, He+, Ne+, and O+ energies from the spacecraft potential to 15 keV using large, high-quality datasets. In this study, we concentrate on He+ ions, whose diagnostics are highly sensitive to ion wave activity. 24 wave events are evaluated, and 15 in which waves were present. A distinction is made between events occurring near, about 3 hours, of noon, and those occurring about 12 hours after noon. For events near the dusk hours, a one to one correspondence between EM waves and heavy ion distributions exhibiting perpendicular component enhancements is found. Distributions from EM waves exhibit a plasma sheet like shape. He++ and Ne++ ions are evidence for the existence of an ion heating phenomenon. For events occurring near noon, a good relationship between EM waves and He++ ions with a similar shape in profile and similar spectral width is noted. The observed frequencies in the ion wave convection zone with the enhanced heavy ion component above 50 keV is attributed to the perpendicular heating of the ions.

$\text{SM22-3}$
1330h
POSTER
Magnetic Field Direction Control of Plasma Wave Emissions in the Earth's Magnetosphere
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Prior to the ISEE-3 encounter with Comet Giacobini-Zinner the spacecraft performed several passes through the field downstream the magnetopause. The magnetopause often contains intense broadband electrostatic plasma wave emissions and often in the form of wave packets with the characteristic signature of the ion and electron plasma frequencies. The ISEE-3 data shows that the waves are often synchronized with the passage of the magnetic field in the downstream direction. This effect is independent of the direction of the field in the plane of the upstream field, with wave emissions diagonal with the field being perpendicular. This effect is independent of the direction of the field in the plane of the upstream field. The characteristic signature of the ion and electron waves in the magnetosphere. The correlation with field direction is less pronounced than in the upstream region, although the wave dropout sometimes correspond with decreases in the magnetic field. It may be the first indication of magnetic field direction influencing the appearance of downstream electrostatic waves.

ORIGINAL PAGE IS OF POOR QUALITY
We have examined Voyager 1.) Smith, polarized waves simultane-ous observation of source of this frequencies Left-Hand linearly polarized, the the upstream plasma velocity!,_e when the upstream plasma velocity v/c < 1. Two processes are important for the nonthermal particle acceleration: one is the relativistic cyclotron resonance between electrons and the magnetosonic waves excited by the gyrating reflected ions. Since the high frequency magnetosonic waves are almost instantly polarized, the electrons can resonate with the waves. Another process is the E x B drift acceleration by the waves of nonlinear steepened magnetosonic waves. The waveslet can tend to diffuse particles within the velocity space.

**SH201-13 1700h**

Linear Damping of Waveshead Upstream Whistler

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Previous studies of upstream whistlers at Venus by Orlofsky et al. [1991] have determined that the plasma waves to the solar wind electrons, such as temperature anisotropy and relative con-fined density ratio. Detailed analysis of the Doppler-shift and the whistler dispersion relation indicate that whistler waves propagate obliquely in a wide band (10-100 times the proton gyrofrequency) in the plasma frame. In this paper we present results of calculations of damping lengths of right-hand whistlers using the form of drift of Maxwellian electron distributions as a best fit to the ISEE 1 electron data. For 30 keV electrons we observe, convergent damping lengths derived from the two spacecraft are consistent with theoretical results. We find that the calculated convective damping lengths vary from about 200 to 2000 km consistent with observations. We also show that the slope of plasma frame spectra of upstream whistlers, observed by direct fitting or by ‘inverse’ phase shifting of the observed spectra, is between 2.5 and 4.5. The spectral characteristics, proximity in the shock as well as propagation and damping properties, indicate that these waves cannot be generated in the solar wind. Instead the observed upstream whistlers in the shock foot and/or ramp must grow by a variety of cross-field drift electron instabilities. Finally we find that in all 3 cases the upstream plasma was quite stable over the frequency range of the observed waves. In fact the waves were strongly damped.

**SH201-11 1630h**

L-W Hertza Pola rized Magnetic Waves at Whistler Mode Frequencies

H K Wong (Department of Space Sciences, Southwest Research Institute, San Antonio, TX 78228-0510, 210-225-5637; SWRI, KRT)

C W Smith (Barat Research Institute, University of Delaware, Newark, DE 07176, 302-831-8114; SPAND-BARTOL/UD/BR/CUCK)

It is shown that an anisotropic electron beam is capable of producing both left and right hand parallel propagating electromagnetic waves with frequencies at the whistler mode range. The physical parameters that determine the instability are the temperature anisotropy, the beam density, and the main of the beam temperature and the temperature of the background plasma. For the physical parameters under consideration, the left-hand wave typically has higher growth rate than the right-hand wave. The free energy source of this instability is the temperature anisotropy but the beam speed can significantly alter the wave frequency. Numerical and analytical calculations will be presented to demonstrate the conditions under which the instability can occur and the possible applications of this instability to whistler waves observed in planetary bow shocks will be discussed.

**SH201-12 1650h**

Whistler Waves Upstream of Neptune’s Bow Shock

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We have examined Voyager 2 magnetometer measurements returned upstream of Neptune’s bow shock in a search for whistler wave activity arising from any of several possible sources. Part of the motivation for this study is the reported obser-vation of unusually intense whistler mode activity upstream of the Uranus shocked1) arising from gyrating proton populations and the excitation of multiple whistler mode waves by energetic electronrel. A recent instability analysis2) has shown that the simultaneous excitation of multiple whistler mode waves is possible over a wider range of plasma and beam conditions than were inferred to exist at Uranus while the excitation of left-hand polarized waves at variable frequency wave functions is also possible3). We have used the available data from the magnetometer waves in Neptune’s bow shock as well as a number of additional whistler mode forms. These reports include the results of a preliminary survey of the magnetic field in Neptune’s bow shock, the detection of whistler waves, and measurements of the upper atmosphere magnetic field in the magnetosheath region.

4) This work was supported by NASA grant NAGW-3445 and Jet Propulsion Laboratory contract #855187 to the BRI.

**SH201-2 0830h**

Collisionless Shock Physics II Poster: Presiding: M Shea, Phillips Lab

**SH201-1 0830h**

Investigation of Bow Shock in a Laboratory Simulated Earth’s Magnetosphere

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Joelshim (Lincoln Laboratory, MIT; 65, Los Alamos, New Mexico 87545; 501-667-9232)

Solar wind interaction with the Earth’s magnetic field is studied in a laboratory simulated magnetosphere by injecting a flowing magnetized plasma with a stationary dipole field. Particular emphasis placed on the interaction of the bow shock and its dependence on the polarity of the IMF. The bow shock is identified by using a gated electrostatic (GOL) and detailed measurements obtained by using two-dimensional magnetic probes, Langmuir probe and double-sided Faraday cup. These techniques are capable of measuring the structure of the bow shock, and the Alfven mach number is larger than unity, a bow shock appears in front of the simulated magnetosphere. The spatial images for different orientations of the IMF. The measurements of the magnetic field, plasma parameters, and the current density are presently underway. These measurements will provide quantitative and detailed information about shock propagation and shock unshocked regions and the type of the bow shock that forms in the laboratory simulated magnetosphere.

*Research supported by NSF and IGRP/LANL.*

**SH201-3 0830h**

Pioneer Venus Orbiter Retarding Potential Analyzer Observations of the Electronic Component of the Solar Wind and Interaction with the Venus Bow Shock Crossings and the Magnetosheath Region

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Using an improved expression for the grid potential distribution for the Retarding Potential Analyzer, a comparison of the suprathermal electrons measured by this instrument with the Plasma Analyzer suprathermal electron data shows differences between the UPRA suprathermal electron observations and the Solar wind electron data. Differences also exist in the electron anisotropy, probably associated with the velocity distribution function of the observed electrons. We will present results of applying this improved technique to observations of the plasma analyzer and auger electron spectrometer data for a mission to study the interplanetary electron distribution function.

**SH201-4 0830h**

Extrapol Plasma Outlines in the Forebomk: Comparison of Occurrence at PV0 and ISEE 3

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Crawford et al. [1993] recently implemented a program to map the occurrence of plasma wave events in normalized coordinates in the Venus Region. We will report on the results of applying this program to ISEE 3 and PV0 data. The program will be made available to the ISEE 3 community for future studies.

**SH201-5 0830h**

Superthermal He+ and the Origin of Energetic Ions in the Earth’s Forebomk Region

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Energetic ion distributions (with energies of a few keV extending to over 100 keV, also called diffuse ion distributions) upstream from the Earth’s equatorial parallel bow shock have approxi-mately equal solar wind composition (i.e., 4% H). In contrast, field-aligned ion beams observed in the forebomk region upstream from the Earth’s bow shock have He% concentrations that average two orders of magnitude below that in the solar wind. While it is clear that field-aligned beams are not the major source of energetic ions in the forebomk region, the ion population (i.e., the suprathermal stage through which the solar wind source particles pass in the acceleration process) for these ions has not been identified. We report B- and B+ observations from the ISEE-1 and -2 spacecraft which suggest

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Plasma Waves Downstream of Weak Collisionless Shocks

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In September 1983 the ISEE 3/I CE spacecraft made a long traversal of the distant dawnside flank region of the Earth's magnetosphere and had many encounters with the low Mach number bow shock. These weak shocks excite plasma wave electric field turbulence with amplitudes comparable to those detected in the much stronger bow shock near the nose region. Downstream of quasi-perpendicular (quasi-parallel) shocks, the E field spectra exhibit a strong peak (plateau) at midfrequencies (1–3 kHz); the plateau shape is produced by a low-frequency (100–300 Hz) emission which is more intense behind quasi-parallel shocks. Polarization measurements made in the very steady magnetic field conditions downstream of two quasi-perpendicular shocks show that the low frequency signals are polarized parallel to the magnetic field, whereas the midfrequency emissions are unpolarized or only weakly polarized. A new high frequency (10–30 kHz) emission which is above the maximum Doppler shift frequency is clearly identified as a separate wave component. High time resolution spectra often exhibit a distinct peak at high frequencies; this peak is often blurred by the large amplitude fluctuations of the midfrequency waves. The high-frequency component is strongly polarized along the magnetic field and varies independently of the lower-frequency waves.

1. Introduction

From September through December of 1983 the ISEE 3 spacecraft traversed the far dawnside region of the magnetosheath and had multiple encounters with the bow shock [Greenstadt et al., 1990]. Since the shock normal is nearly orthogonal to the solar wind flow direction, the far flank shocks have low Alfvén and magnetosonic Mach numbers. Thus the ISEE 3 data set provides a unique opportunity to investigate the plasma, magnetic field, and plasma wave properties of collisionless shocks in a Mach number regime which has rarely been accessible to previous satellite studies. In this paper we focus on plasma wave electric field measurements in the region immediately downstream of several typical quasi-parallel and quasi-perpendicular flank shocks. Strong shocks in the nose region of the magnetosheath [Rodriguez and Gurnett, 1975] and interplanetary shocks [Kennel et al., 1982] generate intense electric field turbulence in the downstream region. The weak flank shocks might be expected to stimulate a significantly lower level of downstream wave noise. We find, however, that the electric field spectral amplitudes and spectral shapes detected behind the flank shocks are quite comparable to the wave properties observed behind the nose region shocks.

In the subsolar region of the Earth's bow shock, Rodriguez [1979] identified three types of electrostatic plasma waves which occurred in the magnetosheath: (1) a low-frequency component with a peak near 100–300 Hz, well below the ion plasma frequency \(2\pi f_{pi} = (4\pi ne^2/m_i)^{1/2}\) and with a smoothly falling spectrum above the peak frequency; (2) an intermediate-frequency component with frequencies between the ion and electron plasma frequencies \(f_{pi} < f < f_{pe}\) and a peak near 1 kHz; and (3) a high-frequency component at the electron plasma frequency. The low-frequency component resembles the wave spectra typically observed within the shock front [Rodriguez and Gurnett, 1975; Gurnett, 1985], whereas the intermediate- and high-frequency components had spectra which are similar to wave emissions in the upstream region. Rodriguez [1979] suggested that the intermediate-frequency waves might be excited by narrow velocity spread electron beams as are believed to cause the similar upstream emissions. By comparing the voltages across antennas with different tip-to-tip lengths, Rodriguez [1979] concluded that the wavelengths of the magnetosheath turbulence exceeded 100 m across the entire frequency band from 40 Hz to 100 kHz. Since IMP 6 had a pair of orthogonal antennas and obtained the full waveform from 0 to 1.0 kHz, Rodriguez [1979] demonstrated that the electric field polarization in this frequency range was parallel to the magnetic field. At higher frequencies, Rodriguez and Gurnett [1975] used rapid sample (a measurement of a given frequency channel every 0.32 s) electric field amplitudes to show that the waves at 3.11 kHz were polarized along the field direction and stated that parallel polarization was a general property of the magnetosheath wave emissions.

Anderson et al. [1982] reported on two additional aspects of magnetosheath waves. Using the high time resolution capabilities of the ISEE 1 and 2 electric field spectrum analyzer and wideband system, Anderson et al. [1982] discussed short-duration emission spikes which spanned the frequency range from 100 Hz to 56 kHz. These spikes are a permanent feature of the nose region magnetosheath and made the main contribution to the spectral density above 1.0 kHz. The HAM passive sounder measurements indicated that the e-folding time of the spikes was less than or comparable to the 8-ms time constant of the HAM receiver. The electric field spectrum analyzer showed that the spikes occurred simultaneously at all frequencies within the 50 ms
<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. DOCUMENT IDENTIFICATION INFORMATION</td>
<td>This section identifies the document with its title, authors, and other relevant information.</td>
</tr>
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</tr>
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<td>This section outlines the handling and disposition of the document.</td>
</tr>
</tbody>
</table>