Upstream Particle Spatial Gradients and Plasma Waves


The upstream electron and ion fluxes detected by our experiment on ISEE 1/2 spacecraft undergo frequent time variations, from a few seconds to minutes. Many flux variations correlate with directional changes of the interplanetary magnetic field (IMF). Particles propagating in the upstream region act on by the solar wind electric field creates a quasi-stationary particle pattern in space. Evidently, the spacecraft frequently crosses the boundaries of these particle patterns. Our analysis strongly suggests that the particle time variations are usually spatial variations that have been convoluted into our data. Estimates of the thickness of the particle boundaries deduced is >1 Larmor radius (for both the upstream electron and the ion events). Plasma waves are observed in association with the upstream particle fluxes and a correlation between the amplitudes and the particle boundaries is suggested. We will theoretically show that the ion and electron density gradients across the boundary play an important role in exciting the ion acoustic-like and plasma waves.

1. INTRODUCTION

Extensive studies of bow shock associated electrons and ions observed in the upstream region exist in the literature [Asbridge et al., 1968; Feldman et al., 1973; Ogilvie et al., 1971; Scudder et al., 1973]. These upstream particles are accompanied by electrostatic noise, the electrons by plasma oscillations [Scarfi et al., 1970], and the ions by ion acoustic waves [Gurnett and Frank, 1978]. Fredricks et al. [1971] have interpreted the correlation of the plasma oscillations with suprathermal electrons and suggest that a two stream instability is responsible. Filbert and Kellogg [1979] support this interpretation. Filbert and Kellogg based their conclusion on observations of close correlation between the detection of the plasma oscillations and the direction of the interplanetary magnetic field (IMF). Waves were detected only when the IMF connected to the bow shock. They interpreted that the connection permits the bow shock electrons to stream outward, thereby exciting the plasma oscillations (by the two-stream instability).

The ISEE 1/2 observations of upstream particles and waves have verified the previous observations but, in addition, have shown new features (see articles, this issue). For example, Gosling et al. [1978] have identified two classes of ion fluxes to populate the upstream region. One appears in a narrow range of pitch angles along the IMF direction traveling away from the shock. This ion beam is believed to be reflected solar wind ion fluxes [Gosling et al., 1978]. The other consists of particles over broad pitch-angle ranges, and this population has been referred to as 'diffuse.' The diffuse population is accompanied by hydromagnetic waves [Paschmann et al., 1979], and the energy spectrum of this component is somewhat harder than that of the reflected component [Gosling et al., 1978].

The plasma characteristics of the energetic upstream electron fluxes are not as well understood at this time. Information on the distribution functions of bow shock associated electrons in the energy range 1 keV has been obtained by Feldman et al. [1973] and Scudder et al. [1973]. However, information on >1 keV electrons (those that are primarily concerned with this article) is still lacking. Limited information available from our particle experiment on ISEE 1/2 spacecraft (our experiment detects electrons and ions at several discrete energies, see below) indicates that upstream electron fluxes frequently occur at ~1.5 keV energies in bursts lasting from a few seconds to several minutes. Typical upstream electron fluxes are extremely weak, and for >1.5 keV energies, they are ~10^4 (cm^2 s sr keV)^{-1} [see Parks et al., 1978].

Both upstream ion and electron fluxes detected on ISEE are accompanied by intense plasma waves [see Anderson et al., this issue, and references therein], the ions by ion acoustic-like waves, and the electrons by high frequency electron plasma oscillations and also by ion acoustic-like waves lower in frequency than those accompanying the ion fluxes. The amplitudes of these plasma waves are considerably enhanced whenever our experiment records large changes of particle fluxes. It will be shown in this paper that these particle flux changes can be related to spatial variations and that the flux changes signify that the spacecraft is crossing a particle boundary. We then study the correlation of wave enhancements at these particle boundaries. It will be shown that these waves can be driven by ion and electron flux gradients (a complete theoretical treatment of this problem will be given in Wu et al. [1980]).

2. DATA ANALYSIS

Upstream electrons. A survey of upstream particle data that included several hundred hours of data obtained when the spacecraft were located between noon and dawn sectors indicates that more than 70% of the electron events are detected primarily in the energy interval ~1.4–1.6 keV. (This is the lowest energy detector of our experiments. A detailed description of our ISEE experiment is given in Anderson et al.)
It suffices to mention here that we detect electrons and ions at discrete energies with high sensitivity and that our detectors are aligned along the spin axis and point southward. The other 30% shows electron fluxes to energies >42 keV (for example, the events studied by Anderson et al. [1979]). A typical example of upstream electron events is shown in Figure 1. The data shown represent high-resolution particle data (32 data points per second). Also shown in Figure 1 are the magnetic field data obtained on the same spacecraft (courtesy of UCLA). During the interval 1530–1607 UT, no detectable ion fluxes were observed by our experiment, indicating the ion fluxes for >1.5 keV energies were <10^6 (cm^2 s sr keV)^{-1}.

The upstream electrons have durations that last from seconds to minutes. The peak flux level is extremely steady for these events and at maximum, it is ~10^6 (cm^2 s sr keV)^{-1}. It can be seen in Figure 1 that the IMF consisted largely of a B_z component in the ecliptic plane. Since the detector looks essentially southward detecting particles moving in the +z direction, this means that for these particles, the pitch-angle distribution in the range ~70°–90° is nearly uniform. The pitch angle defined by tan S = V_x/V_z is deduced every 5 s in the interval 1530–1600 UT shows that during this interval, our experiment detected electrons with ~70°–90° pitch angles (not shown). We now demonstrate below that electron fluxes decrease (for example, at 1540 UT) because the IMF changes direction, which puts the spacecraft on lines of force not connected to the shock surface. Our analysis given below follows the approach outlined in Filbert and Kellogg [1979].

Consider an upstream particle with a velocity V and a pitch-angle α propagating in the solar wind. This particle will be convected in the direction perpendicular to the interplanetary magnetic field B, due to the solar wind electric field. If B were uniform and the particles were not subject to other forces, the guiding center velocity V_{gc} of the particle is V_{gc} = V_x + V_{drift} where the parallel refers to the direction relative to B and V_{drift} = |V_x| cos α. Here α is the particle pitch angle. V_{drift}, the drift velocity, is due to the solar wind and is \( E \times B / B^2 \). The magnitude of V_{gc} is \( |V_{gc}| \) sin φ, where φ is the angle between V_{gc} and B. We now apply these equations to our data.

Our studies are conducted in a frame in which the IMF and the position vector of the spacecraft are in the same plane (see Figure 2a, 2b, 2c). To obtain this geometry, we first rotate the IMF measured in the GSE system about the X axis so that IMF is now in the XZ plane. We then translate the spacecraft position vector in the Y direction (in the new system) so that the spacecraft and the IMF are in the same plane. Another rotation about the Y axis is made so the IMF is along the Z axis. One can then compute where on the bow shock surface the observed IMF intercepts it (the shape of the bow shock is assumed to be a paraboloid as described by Filbert and Kellogg [1979]). A parameter D can be defined which measures the distance on the X axis where the observed IMF intercepts the point of tangency on the surface. Particles leaving the shock at this point will make an angle δ with the direction of IMF:

\[
\tan \delta = V_x/V_{ni}
\]

or

\[
\tan \delta = V_{gc} \sin \phi / V_{cos} \alpha
\]  

(1)

These particles will be detected by a spacecraft if the spacecraft is located at a point in space such that the particle propagation vector (given by (1)) intercepts the spacecraft. Since tan δ is inversely proportional to the particle parallel velocity, higher energy particles make smaller angles than the lower energy particles. If we assume that particles of all energies are emitted from the origin, an energy-dependent particle pattern is formed in space and the spacecraft is immersed in this particle pattern.

At a given location in space, the spacecraft will detect particles according to (1). Given that a spacecraft were detecting particles with a certain δ, the spacecraft will also be able to detect particles with smaller δs (higher energy particles) if these particles were emitted by the shock. Particles with larger δ will not be detected because these particles are swept farther downstream of the spacecraft by the solar winds.

The above analysis indicates that if our particle data could be correlated and organized by the directional changes of IMF and by (1), the indications are that we are detecting spatial variations. Below we show electron and ion data that demonstrate these spatial features.

The time variations of electron fluxes in the interval 1530–1605 UT have been compared to the behavior of the spatial parameters D (Figure 3). Here zero represents the 'nose' position of the shock placed for this calculation at X = 15 R_{e} (position observed earlier by ISEE on the same day). Since the parameter D measures the distance on the X axis where the IMF that passes through the spacecraft intercepts the X axis from the point of tangency on the bow shock surface, positive D means the IMF intercepts the X axis inside the position of the nose, and negative D means the IMF crosses the X axis beyond the nose position. Figure 3 shows that electron fluxes are detected when D is positive or nearly positive, and electron fluxes decrease below detection level when D is negative or making a negative excursion. The interpretation of this correlation is that electron fluxes are detected by the spacecraft only when the IMF, while passing through the spacecraft, intercepts the shock surface. Similar results have been reported for the lower energy electrons [Feldman et al., 1973; Scudder et al., 1973].

The solar wind speed during our observational period was about ~280 km/s and φ ≈ 67°. For ~1.5 keV electrons with 70°–90° pitch angles, δ computed from (1) is about 5°. Hence, according to (1), the spacecraft is allowed to detect electrons with propagation angle ±5°.

The results we have just obtained indicate ~1.5 keV electrons fluxes appear and disappear because of the IMF variations and are in agreement with the earlier wave results [Filbert and Kellogg, 1979]. The analysis suggests that the spacecraft is crossing a spatial particle boundary when fluxes increase or decrease. The particle boundaries sweep by the spacecraft when the IMF abruptly changes direction. The thickness of the boundary can be estimated by noting the solar wind speed was about 280 km/s, and the flux changes occur in a few seconds of time. The boundary thickness is then estimated to be ±100 km. The electron gyro-radius of ~1.5 keV electrons in a ~10 gamma field is ~60 km.

The above model predicts presence of higher energy electrons (corresponding to smaller δ values) had these electrons been emitted by the shock. Our ~5 keV detector showed very small increases of electron fluxes, and no detectable increases were seen above this energy. The absence of high energy electrons means that the shock was not emitting these particles, or the fluxes were below the sensitivity of our instrument ±10^5 (cm^2 s sr keV)^{-1} during our observations. One can interpret that the bow shock acceleration was limited to emitting elec-
Fig. 1. High resolution electron and magnetic field data of a typical upstream event. Electrons are detected only when IMF intercepts the shock surface. The flux variations represent spatial variations of fluxes that have been convoluted into our data. See text for further explanations.
energies \(1.5\) keV. Measurements have extended this spectral form down to proton studied by Lin et al. [1974], nearly 6 years ago, and our mea-

This power law form describes the higher energy protons energy spectrum can be described in terms of \(E^{-3.6}\) (Figure 5). For example, the fluxes have "flat top" appearance, and the en-

We conclude this section of the analysis by showing in Figure 4 a short segment of data when upstream electron fluxes were detected in all of our energy channels (up to \(\geq 42\) keV). Higher resolution data (not shown) indicate that the spacecraft detected higher energy electrons first and subsequently the lower energy ones, in accordance with (1). Many examples of this behavior are given in Anderson et al. [1979]. Figure 5 shows a four-point estimate of the electron energy spectrum derived from these events. The energy spectrum can be fitted by a power law, \(E^{-3.6}\). This energy spectrum represents a rough estimate since no attempt was made to correct for Compton-Getting effects. (However, this correction, which will harden the spectrum, is only a few percent.) The significance of this spectral form is not understood. We note, how-

Upstream ions. The upstream ions (for the analysis to follow, we will assume that the ions are predominantly protons), like the upstream electrons, are also organized by the solar wind electric field. Our instrument on ISEE 1/2 frequently detects protons with \(-1.5\) keV to \(\geq 290\) keV energies in the upstream region. The general characteristics of \(\geq 19\) keV protons are similar to the ones studied earlier by Lin et al. [1974]. For example, the fluxes have a "flat top" appearance, and the energy spectrum can be described in terms of \(E^{-3.6}\) (Figure 5). This power law form describes the higher energy protons studied by Lin et al. [1974], nearly 6 years ago, and our measurements have extended this spectral form down to proton energies \(-1.5\) keV.

An example of an upstream proton event detected on November 22, 1977, is shown in Figure 6. This event was detected just ahead of the shock. At \(-0630\), the IMF turned from \((B_r \approx 3\gamma, B_t \approx 3\gamma, B_z \approx 1\gamma)\) to \((B_r \approx 3\gamma, B_t \approx 0\gamma, B_z \approx 3\gamma)\) which provided the connection geometry. The higher energy protons were detected first. This result can be interpreted again by use of (1). \(8\) deduced at \(0630\) UT by using \(V_{sw} \approx 310\ km/s\) (J. Gosling, private communication, 1980) and \(\phi \approx 53^\circ\) (deduced from UCLA data) for \(-50\) keV protons is \(-9^\circ\) for \(-24\) keV protons \(-12^\circ\), and for \(-6\) keV protons \(-24^\circ\). These results predict that the higher energy boundaries will be first detected as the particle pattern sweeps by the spacecraft. (We have ruled out as unlikely that the observed time difference is due to time differences arising from the different propagation times of the protons. The spacecraft was \(-1\) Re from the shock surface. Maximum observed time delay of \(-20\) and \(40\) keV protons would have been \(-\leq 1\) s).

On November 8, 1977, the ISEE spacecraft encountered up-
stream proton events typically associated with a quasi-parallel bow shock structure. Figure 7 shows in high time resolution two energy channels of our proton detector and the UCLA magnetic data plotted to the same time scale (protons here were detected at \(\geq 290\) keV energies, not shown). There is a considerable amount of time variation in both sets of data and the particle and wave data appear to be correlated but in a complicated way. The magnetic oscillations are left-hand elliptically rotating waves (C. Russell, private communication, 1980) and are probably the same type of waves observed by Paschmann et al. [1979] in association with "diffuse" events. Like the events studied by Paschmann et al. [1974], this event was preceded by an ion beam confined in a narrow pitch-angle range in the time interval that preceded the first detec-
tion of the particles at \(-2112:40\) UT. (We did not detect the reflected beam because they were outside the field of view of our detection system.) However, note that at the onset of the event, the 1.3--1.7 keV particles were spin modulated (those sharp spikes in 1.3--1.7 keV energy particles at \(-2112:40\)). This spin modulation means the distribution function of these particles had a large gradient in the velocity space, and apparently, the reflected beam momentarily appeared in our detec-
tors as the IMF rotated. Gurgiolo et al. [this issue] have analyzed in detail the characteristics of particle spin modulation and discuss how plasma parameters can be deduced from such observations.

We will not attempt to interpret all of the features visible in Figure 7. It should be noted, however, that the proton fluxes appeared in response to a temporary reorientation of the aver-
age IMF between 2112 and 2124:30 UT. The reorientation ex-
od the instrument to conditions associated with the up-
stream particle region commonly occupied by the ULF waves and diffuse ions. Figure 8a, 8b, and 8c are a series of computer sketches showing the relationship of the shock surface and the spacecraft (indicated by a small circle) to the local reflected beam (R) and diffuse ion boundaries (D). For a full ex-
planation of the figures, the reader is referred to Hoppe et al. [this issue] and Greenstadt et al., 1980. In Figure 8a, the space-
craft lay between the nominal beam and the diffuse boundary; in Figure 8b, which was computed for the IMF at 2112 UT, but which also confirms essentially to the average IMF throughout the wave interval, the field was more nearly close to the local shock normal, the beam was moved far to the shock flank, and the spacecraft was deep in the diffuse/ULF region ahead of the quasi-parallel shock; in Figure 8c, the
Fig. 3. The flux variations are correlated to two parameters, D and δ. +D means IMF intercept the shock, and −D means IMF does not connect to the shock surface. A particle propagating along the IMF direction is displaced by an angle δ due to the solar wind electric field. During the interval shown, particles with δ ≥ 5° will be detected.
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Fig. 4. Examples of upstream electron events showing bow shock accelerated electrons to ≈42 keV energies.

spacecraft was upstream even from the nominal reflected beam.

Our main interest is to emphasize that many of the particle fluxes are actually spatial variations. For example, at the termination of the particle event around 2123:20 UT, the magnet field was fairly steady (Figures 7 and 8c). The signatures here support the picture that a particle boundary was crossed at the termination of the event at 2123:20 UT: the 5.4-6.6 keV proton boundary was detected ~10 s longer than the 1.3-1.7 keV boundary. Recall that this feature is consistent with the prediction of (1). Assume that the particle boundary sweeps by the spacecraft at the solar wind speed (280 km/s). The proton fluxes drop to below the detection level in a few seconds of time, giving an estimated thickness of the proton boundary of about 250-1000 km. This dimension is comparable to the Larmor radius of 1.5 keV protons in 10° field.

The variations of particle fluxes during the magnetic oscillations are not as easy to interpret. In part, the reason is that some of the magnetic variations occur more rapidly than the gyroperson of protons (~10 s). During such intervals, the particle dynamics are not describable by the adiabatic theory, and our method is not applicable. It is beyond the scope of the present study to discuss the behavior of particles in such a rapidly changing magnetic field. However, during slower oscillations, there are particle signatures that are consistent again with the predictions of (1). For example, note the profiles at 2117 UT and 2218:40 UT. The higher energy protons in both of these instances lead the low energy fluxes (we have also examined the 19 keV and 42 keV proton channels and observed that these energy protons are detected even earlier (not shown)). Our conclusion is that some of the particle fluxes changes encountered during slow magnetic oscillations are due to the crossing of the particle boundaries by the spacecraft.

The difficulty of demonstrating these spatial variations during the event arises from the presence also of temporal variations. For example, when the relative intensities in the two energy intervals change (2116:15 UT), the energy spectral hardness of upstream protons is being changed. This observation can be interpreted to mean that the shock acceleration mechanism is extremely dynamic as changes in spectral hardness can be seen to occur in a few seconds of time. Another feature is the spin-modulated fluxes. Spin modulations come and go during the entire duration, sometimes in the 5.4-6.6 keV channel alone (2114:40 UT) and sometimes in the 1.3-1.7 keV channel. Our interpretation is that these result from the existence of large gradients of the particle distributions in the velocity space and suggest that the shock acceleration mechanism is complicated, producing (by mechanisms as yet unknown) several types of particle distributions. The patchy nature of diffuse ion distributions, of which our instrument samples a slice in energy and direction, can be seen in the report of Eastman et al. [this issue].

The role played by the temporal variations can be appreciated here by inspecting Figure 8d. The IMF components for Figure 8d were taken at the peak of the sharp positive excursion in $B_z$ just after ~2113 UT in Figure 7. The figure shows that the satellite was temporarily upstream from both the beam and the diffuse region. There were other such excursions of the IMF later. Yet, there is no indication in the wave train of Figure 7 that there was any emergence from the ULF region between its onset at 2112:30 UT and its termination at 2124:30 UT. Thus, some of the wave particle activity in Figure 7 was of local and transient nature and not totally related to the spatial structure that must have existed overall.

A question of considerable interest to us is whether the ions that are detected are in any way associated with the genera-

Fig. 5. A four point energy spectrum of electrons and ions detected by our experiment in the upstream region. The electron spectrum is $\sim E^{-1.8}$ and the ion spectrum is $\sim E^{-2.6}$. 
tion of the (ULF) hydromagnetic waves. We cannot answer this question adequately at this time. However, in view of the fact that our observations can be fairly well explained with the adiabatic theory as prescribed in (1), we believe that the observed particle variations are primarily spatial and do not require more complex explanations that may involve temporal variations of the distribution function (except for short intervals when temporal variations are clearly identified). The ion fluxes are modulated simply because the IMF variations cause the spacecraft to enter different regions of the particle spatial pattern.

Enhancement of upstream plasma waves near particle gradients. It has been known since the observations by Scarf et al. [1971] and Gurnett and Frank [1978], that the upstream particles are associated with plasma waves. The ISEE 1/2 wave and particle experiments have corroborated these early observations. Eastman et al. [this issue] have discussed the details of the three dimensional plasma characteristics during these wave observations. Anderson et al. [this issue] have discussed the details of the associated plasma waves and the correlation of these waves to the particle data. The main purpose of this section is to present theoretical support that the ion and electron flux gradients that we detect may play an important role in the excitation of these upstream waves.

Figure 9 shows the upstream electron data shown earlier in Figure 1 together with the University of Iowa plasma wave data. Figure 10 shows the upstream ion data shown in Figure 7 together with the plasma wave data. These figures suggest that the plasma wave amplitudes might be enhanced when there are large changes in the particle fluxes. We have looked into the possibility how the observed proton and electron gradients could enhance the plasma waves. Below, we show theoretically that the few keV particle gradients could contribute toward exciting waves with frequencies ranging from that of the ion sound waves to that of the Langmuir waves. (It is appropriate to point out here that a proper way to establish whether a correlation exists between two sets of noisy particle and wave data requires that a statistical analysis be per-
formed. This analysis will be made, and when the results are available, they will be reported.) To facilitate our discussion we introduce a coordinate system in which the density gradient of the energetic particles is in the X direction and the ambient magnetic field $B_0$ is parallel to the Z axis. The solar wind plasma is considered to be homogeneous. In view of the fact that the plasma waves might be excited by a small population of energetic particles, these waves must be weakly damped when the upstream particles are absent. Thus, we shall pay special attention to those modes which are easily excitable by the density gradient effects in the appropriate frequency ranges. We suggest three wave modes which are relevant.

1. Mixed ion-electron oscillations with frequencies above the lower-hybrid frequency. These waves satisfy the following dispersion relation

$$\omega^2 = \frac{\omega_i^2 + \omega_e^2 \cos^2 \theta B_0 e^{-\eta}}{1 + (2\omega_i^2/k^2\nu_e^2)(1 - I_0 e^{-\eta})}$$

$$\approx k^2 c_s^2 + (\nu_e^2/2) \cos \theta B_0 e^{-\eta/\nu_e^2},$$

where $\omega_i$ and $\omega_e$ are the ion and electron plasma frequencies, respectively; $c_s = (T_i/m_i)^{1/2}$ is the ion sound speed; $\nu_e = (2T_e/m_e)^{1/2}$ is the electron thermal speed; $I_0 = I_0(\mu_e)$ is the zeroth order modified Bessel function; $\mu_e = k_e^2 \nu_e^2/2\Omega_e^2$; and $\Omega_e = [eB_0/m_e c]$ is the electron gyrofrequency. The mode is weakly Landau damped, because for $\mu_e < 1$ and $\omega_i^2 \gg \Omega_e^2$, where $\omega_i$ and $\omega_e$ are the ion and electron plasma frequencies, respectively; $c_s = (T_i/m_i)^{1/2}$ is the ion sound speed; $\nu_e = (2T_e/m_e)^{1/2}$ is the electron thermal speed; $I_0 = I_0(\mu_e)$ is the zeroth order modified Bessel function; $\mu_e = k_e^2 \nu_e^2/2\Omega_e^2$; and $\Omega_e = [eB_0/m_e c]$ is the electron gyrofrequency. The mode is weakly Landau damped, because for $\mu_e < 1$ and $\omega_i^2 \gg \Omega_e^2$, where $\omega_i$ and $\omega_e$ are the ion and electron plasma frequencies, respectively; $c_s = (T_i/m_i)^{1/2}$ is the ion sound speed; $\nu_e = (2T_e/m_e)^{1/2}$ is the electron thermal speed; $I_0 = I_0(\mu_e)$ is the zeroth order modified Bessel function; $\mu_e = k_e^2 \nu_e^2/2\Omega_e^2$; and $\Omega_e = [eB_0/m_e c]$ is the electron gyrofrequency.

2. Ion sound waves with frequencies close to the electron gyrofrequency or its harmonics. For the cases studied, the solar wind ion density was $15 \text{ cm}^{-3}$ and the ambient magnetic field was $8 \gamma$. Thus, the typical ion plasma frequency is about $810 \text{ Hz}$, and the electron gyrofrequency is about $220 \text{ Hz}$. Consequently, when we discuss ion sound waves, the effect of magnetized electrons should be taken into consideration. For nearly perpendicular propagation, the dispersion equation may be written as

$$1 + k^2 \lambda_i^2 + \frac{T_i}{T_e} [1 + \xi(Z(\eta_i)) + \frac{n_i}{n_e} \frac{T_i}{m_i \alpha_i^2} [1 + \eta Z(\eta_i)]$$

$$= \frac{\omega^2}{k^2 \nu_i^2} \left\{ \frac{n_e}{n_i} \frac{\omega_i^2}{\alpha_i^2} \right\}$$

$$- \frac{\omega}{k \nu_i} \left[ \exp \left( -\frac{\omega^2}{k^2 \nu_i^2} \right) + \frac{k}{k_1} \left( \frac{m_e}{m_i} \right)^{1/2} \frac{T_i}{T_e} \exp \left( -\frac{\omega^2}{k_1^2 \nu_i^2} \right) \right\} \left( 1 + \frac{n_i}{n_e} \right)$$

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where $n_i$ and $n_e$ denote the densities of the energetic (~keV) protons and the solar wind protons, respectively; $V$ and $\alpha_i$ are the streaming velocity and random velocity of the energetic protons; $\omega_i = (n_i^{-1}) \partial n_i / \partial \xi$; $\rho_i = \alpha_i / \Omega_i$ is the gyroradius of the energetic protons; and $k_i$ is the y component of the wave vector $k$. From (3) we find that the condition for excitation is

$$|k_i V + k_e \rho_e \alpha_e / 2| > \omega \left[ 1 + \frac{n_e}{n_i} \frac{\alpha_i^2}{\nu_i^2} \right] \times \left\{ \exp \left( -\frac{\omega^2}{k^2 \nu_i^2} \right) \right\}$$

$$+ \frac{k}{k_1} \left( \frac{m_e}{m_i} \right)^{1/2} \frac{T_i}{T_e} \exp \left( -\frac{\omega^2}{k_1^2 \nu_i^2} \right) \right\} \left( 1 + \frac{n_i}{n_e} \right)$$

We find that this condition can be satisfied if we consider $(n_i/n_e) = 10^{-2}$, $\alpha_i^2/\nu_i^2 \approx 10^{-2}$ (i.e., upstream ions are of 1 keV) and other parameters compatible to observations. However, it should be remarked that these waves have frequencies below that of the ion sound waves. Moreover, their wavelengths are very long in comparison with Debye lengths.

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$$= \frac{\omega^2}{k^2 \nu_i^2} \left\{ \frac{n_e}{n_i} \frac{\omega_i^2}{\alpha_i^2} \right\}$$

$$- \frac{\omega}{k \nu_i} \left[ \exp \left( -\frac{\omega^2}{k^2 \nu_i^2} \right) + \frac{k}{k_1} \left( \frac{m_e}{m_i} \right)^{1/2} \frac{T_i}{T_e} \exp \left( -\frac{\omega^2}{k_1^2 \nu_i^2} \right) \right\} \left( 1 + \frac{n_i}{n_e} \right)$$

where $\xi = \omega / k_1 \nu_i$, and $\eta = (\omega - k \rho_i) / k \alpha_i$; $A_\rho = e^{-\eta} I_n(\mu_e)$; $Z$ denotes the usual plasma dispersion function.

The third term represents the contribution of the upstream protons. For simplicity we have assumed that the distribution
Fig. 9. High resolution electron and plasma wave data. Note the 'burry' nature of both sets of data. The wave amplitudes appear to be enhanced at the 'edges' of particle fluxes.
Fig. 10. High resolution ion and plasma wave data. The wave amplitudes are enhanced when the particle flux changes considerably, across particle gradients.
function of the energetic protons may be approximated by a displaced Maxwellian distribution. The growth rate may be readily calculated. The condition for excitation is

$$\frac{n_c}{n} \frac{\alpha_e^2}{\alpha_p^2} \left( \frac{k_e \rho_p \alpha_e}{2} \right) > \frac{\alpha_p}{\omega_p} \exp \left( -\frac{n^2 \Omega_p^2}{k^2 v_p^2} \right)$$

(6)

The wavelengths of interest to us satisfy the inequalities $k \lambda_e^2 < 1$ and $k \lambda_p^2 \gg 2 \Omega_e^2$ where $\lambda_e$ is the Debye length. Of course, in addition we require $n^2 \Omega_p^2 > k^2 v_p^2$ so that ion Landau damping is very small. In short we find that (6) can be easily satisfied with parameters compatible with observations. A detailed discussion is presented in a separate paper [Wu et al., 1980].

Although in (6) we have only considered upstream ions, it can be shown that the density gradient of the upstream electrons may also excite the aforementioned waves. This point can be discussed in a somewhat similar manner. However, in this case the upstream energetic electrons must be considered to be magnetized. Their contribution to the dispersion equation can be easily derived from existing theory [Mikhailovskii, 1974].

3. Electron Langmuir waves with frequencies much higher than the gyrofrequency. For these high frequency waves, the dispersion relation takes the form

$$\omega^2 = \omega_e^2 + \frac{3}{2} \alpha_e^2 k_x^2$$

(7)

where $k_x$ denotes the component of $k$ perpendicular to the ambient magnetic field $B_0$. In this case the upstream ions cannot excite these waves, because the necessary condition for excitation

$$|k \cdot V + k_e \rho_p \alpha_e / 2| > \omega$$

(8)

cannot be satisfied. An explanation is in order. First, the observational result described earlier indicates $\epsilon_p \sim 0(1)$. Thus (8) implies roughly

$$|k \cdot V| + |k \alpha_e / 2| = |k \alpha_e| > \omega$$

(9)

Here we have assumed that $k \cdot V$ and $k \alpha_e / 2$ are of the same order of magnitude. However,

$$\frac{k \alpha_e}{\Omega_e} \approx \frac{\mu_e^{1/3} \alpha_e}{\nu_e}$$

(10)

and

$$\frac{\omega}{\Omega_e} \approx \frac{\omega_e}{\Omega_e}$$

(11)

For electron Langmuir waves with $k \lambda_e < 1$, we find

$$\mu_e^{1/3} < \frac{\omega_e}{\Omega_e}$$

(12)

From (10), (11), and (12) we see that condition (8) or (9) is not satisfied since $\nu_e > \alpha_e$. Hence we shall only consider the effect of energetic electrons which have a density gradient $\epsilon'$ ($\epsilon' = 1/n, dn_e/dx$). The condition for excitation is

$$|k \cdot V + k \epsilon' \rho_p \alpha_e / 2| > \omega \left[ 1 + n_e \frac{\alpha_e^3}{\nu_e^2} \exp \left( -\frac{\omega_e^2}{k^2 v_e^2} - \frac{3}{2} \right) \right]$$

(13)

Observational results discussed in the preceding section indicate $\epsilon' \rho_p$ is roughly of order unity. For $\omega_e^2 / k^2 v_e^2 \sim 10^{-2}, n_e/n, \sim 10^2$, and $V \ll \alpha_e$ (13) reduces to

$$\left| \frac{k \alpha_e}{2} \right| > \frac{\omega_e}{\Omega_e}$$

(14)

which can be satisfied easily as long as $k \lambda_e < 1$. Again the details will be discussed in a separate paper by Wu et al. [1980].

To summarize we conclude that both the diamagnetic crossfield drifts associated with the upstream ions and electrons can result in the excitations of plasma waves. However, the inhomogeneous energetic ions cannot excite the high frequency Langmuir waves, whereas the electrons can excite both ion sound waves near electron cyclotron harmonics and Langmuir waves. For the lower frequency waves, the typical phase velocity is several times the ion thermal speed. Thus, the Doppler shift in the satellite frame may be significant. However, for the high-frequency Langmuir waves, the Doppler effect is expected to be negligible.

Finally, we remark that waves with frequencies as high as 100 kHz have been observed as shown in Figure 9. In the present case the electron plasma frequency is estimated to be slightly below 37 kHz for $n_e \sim 15 \text{ cm}^{-3}$. It is not clear to us what is the nature of those waves with $f > 31.1 \text{ kHz}$. One possible explanation is that these waves may have frequencies much lower than the plasma frequency but are significantly Doppler shifted. Whether this explanation is reasonable remains to be studied.

3. CONCLUSIONS

The analysis of the bow shock accelerated upstream electron and ion events has led us to conclude that our data can be organized within a framework of a simple model in which the particles propagating in the upstream region are acted on by the solar wind electric field. The spacecraft is immersed in a particle pattern and the energy of the particles the spacecraft can detect is governed by (1). When the solar wind velocity and/or the magnetic field direction changes, the spacecraft will travel through this particle pattern and as a result will cross different energy particle boundaries, subject also to local temporal dynamics. Many of the flux changes that we detect are consequences of such boundary crossings, and we have deduced that these boundaries are extremely sharp (~Larmor radius).

Wave-particle correlation data indicate that both electron and ion associated plasma waves are enhanced across these particle boundaries. We suggest that the diamagnetic drifts associated with the density gradients of the upstream particles can be the cause of excitation. Theoretically, we find that upstream ions cannot excite Langmuir waves because the frequencies are too high to satisfy the condition for excitation. However, the upstream electrons can excite both low and high frequency waves. This finding is consistent with observations shown in Figures 9 and 10.

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