OBSERVATIONS OF SHOCK ACCELERATION PROCESSES IN THE SOLAR WIND

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1. Introduction. Substantial evidence has been accumulated over more than two decades that ion acceleration occurs at all collisionless shocks sampled directly in our solar system. Figure 1 (after Gloeckler, 1984) shows schematically the various shock waves in the heliosphere and the associated energetic particle phenomena. Three shocks have attracted considerable attention in recent years: corotating shocks due to the interaction of fast and slow solar wind streams during solar minimum, travelling interplanetary shocks due to coronal mass ejections and planetary bow shocks. We will review briefly the signatures of these shocks and of their energetic particles, will shortly review the most prominent theoretical models for shock acceleration and discuss in more detail recent observations at the earth's bow shock and at quasi-parallel interplanetary shocks.

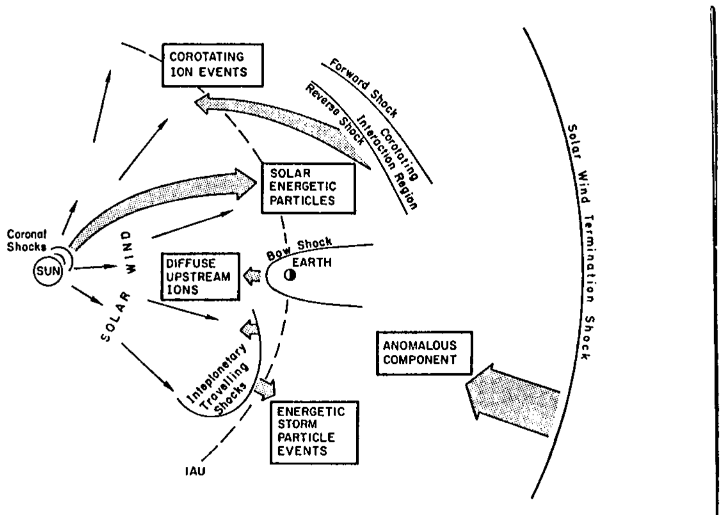

Fig. 1 Heliospheric shocks and associated particle events (after Gloeckler, 1984)

2. Corotating Interaction Regions and Associated Particle Events. During solar minimum the most prominent structures of the interplanetary medium are the high and slow velocity streams. The high velocity streams are presumably originating from polar coronal holes which extend during solar minimum at certain longitudes across the solar equator so that regions with emerging high and slow velocity solar wind are distributed at the solar equator in longitude. Due to the rotation of the sun a high velocity stream following a slow velocity stream will run into the slow velocity stream. Beyond a distance of about 1.5 AU a pair of shocks develop at the inner and

outer edges of the interaction region between high and slow velocity stream (Fig. 2). One of the shocks (running into the slow solar wind) is a foreward shock which propagates out from the sun. The other half of the shock pair is a reverse shock, so-called because it travels backward toward the sun in the solar wind frame. The position of double peaks in recurring energetic ion increases coincides more or less with the appearance of these foreward and reverse shocks (Barnes and Simpson 1976; Tsurutani et al., 1982). McDonald et al. (1976) and Van Hollebeke et al. (1978) have studied the increase of these events with increasing distance in the heliosphere. The distribution functions of protons, He, C, N, O, and Fe can all be very well represented by an exponential in velocity with nearly equal e-folding speeds for all elements in a given corotating event (Gloeckler et al., 1979). Before leaving the topic of corotating particle events we should like to mention that recently Richardson (1985) has presented evidence that in the interaction region within 1 AU, i.e. when the shocks have not developed yet, second order Fermi acceleration accelerates suprathermal solar wind ions up to ∼ 300 keV.

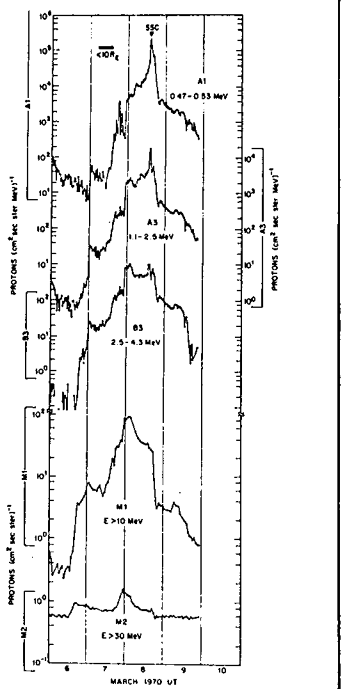

Fig. 2 Typical energetic storm particle event as observed at different energies (Lanzerotti, 1974).

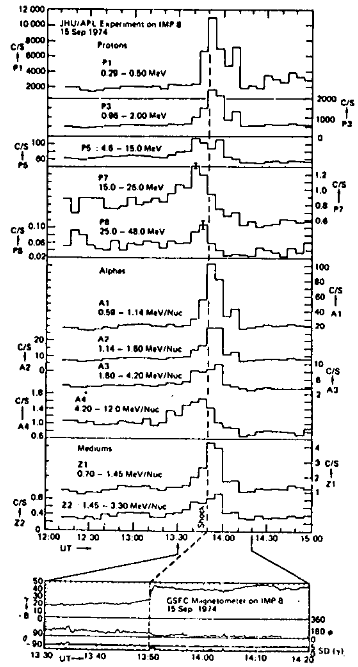

Fig. 3 Intensity vs time for a shock spike event (Sarris et al., 1976).

3. Interplanetary Travelling Shocks. Interplanetary travelling shocks are usually observed as fast mode foreward propagating (with respect to the solar wind frame of reference) shocks and are produced by coronal mass ejections. It has been known for more than two decades that the arrival of a travelling shock at the Earth is often accompanied by large enhancements of energetic solar flare particles. These events have been termed energetic storm particle (ESP) events since they often occur in connection with a sudden storm com-

mencement at Earth (SSC). The effect of the shock wave in altering the profiles of energetic particles can be seen from Figure 2 (Lanzerotti, 1974). Plotted in Figure 2 are proton fluxes measured on Explorer 34 in several different energy channels. The profile of the > 30 MeV protons indicates that two flares are responsible for the energetic particles measured during this time interval. In the lower energy range the second event deviates strongly from a simple diffusive profile and in the lowest energy channel the profile is actually dominated by the particles associated with the SSC. The duration of the ESP events is in the 1 MeV energy range typically of the order of several hours. Recently, new information on acceleration at quasi-parallel interplanetary travelling shocks in the energy range below a few hundred keV have become available from the ISEE-3 spacecraft. This is important since only for particles of this energy the acceleration time is less than (or comparable to) the shock travel time to 1 AU, so that only in this energy range detailed comparison with the predictions of the steady-state quasi-linear theory of diffusive shock acceleration can and should be made.

A different category of shock associated particle increases are the so-called shock spike events. They last typically only several minutes up to half an hour around the shock passage. Figure 3 from Sarris et al. (1976a) shows a shock spike event which extends to very high energies. Sarris and Van Allen (1974) have shown that shock spike events occur in connection with quasi-perpendicular shocks. They explained the shock spike events by an acceleration of solar flare particles in terms of a displacement along the interplanetary electric field during reflection at the shock.

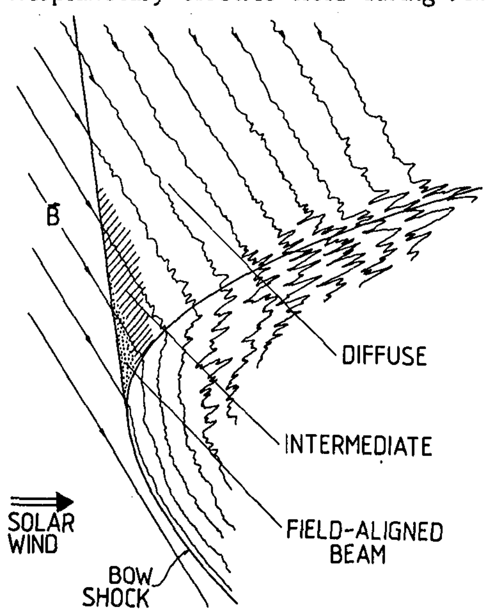

Fig. 4 Average spatial distribution pattern of diffuse ions, intermediate ions, and field-aligned beams relative to the magnetic field-bow shock geometry.

4. The Earth's Bow Shock. Since the solar wind approaches a planetary obstacle with a supersonic speed planetary bow shocks will occur in front of planets with an intrinsic dipole field or with conducting atmospheres. Along a planetary bow shock the angle θ_{Bn} between the magnetic field and the shock normal changes from 90° (at the position where the magnetic field first touches during its convection with the solar wind the bow shock) to 0° (see Figure 4). Furthermore, the region upstream of the quasi-perpendicular part

of the bow shock will be convected with the solar wind into the quasi-parallel part of the shock. Any process which depends on field line connection time, as diffusive shock acceleration, will therefore be only observed at and beyond the quasi-parallel bow shock, since here connection times are longest.

Gosling et al. (1978) have shown that in the lower energy range (below ~ 30 keV) there exist distincly different populations in the upstream region of the Earth's bow shock into which these ions can be grouped. These ions have been called reflected and diffuse bow shock ions, respectively. Reflected ions were originally identified as beams of particles travelling upstream along the interplanetary magnetic field and are found predominantly in the quasi-perpendicular bow shock regime. Diffuse ions, predominantly observed in the quasi-parallel regime, extend to much higher energies and their angular distribution is more nearly isotropic. Figure 5 shows to the left relief plots of upstream ion distributions in the v_x, v_y plane (Paschmann et al., 1981). The isolated peak in the middle is the solar wind distribution. The distribution at the top shows a beam of upstreaming ions, which is almost parallel to the magnetic field. Paschmann et al. (1981) have shown that the energy of the beams is correctly predicted by the assumption of reflection under conservation of the magnetic moment, as first proposed by Sonnerup (1969). Alternative models for upstream beams have been proposed, whereby gyrating ions in the foot of the quasi-perpendicular shock are convected downstream, are pitch-angle scattered by self-excited electromagnetic ion cyclotron waves and can escape again back upstream parallel to the magnetic field (Tanaka et al., 1983).

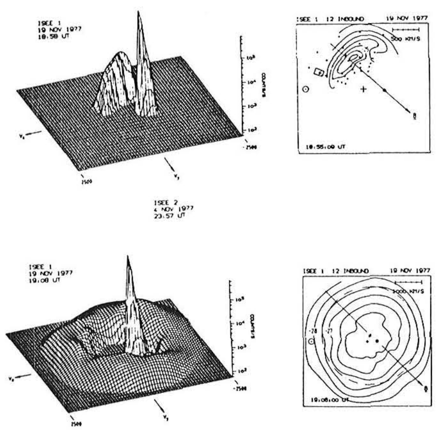

Fig .5 Left hand side: relief plots in 2-dimensional velocity space. Right hand side: contours of const. phase space density for the same events (Paschmann et al., 1981).

Figure 5 shows in the lower part a relief plot of ion distributions found upsteam of the quasi-parallel bow shock. This ion distribution is not beam-like, but is a broad ring-shaped feature or ridge, centered near the origin, with a steeper inner slope and a more gradual slope towards larger velocities. These ions are called diffuse ions since the distribution is more or less isotropic in a frame somewhere between the bow shock frame and the solar wind frame.

Spectra of diffuse ions extend into the higher energy range, i.e. up to 100 keV and higher. Ipavich et al. (1979) and Scholer et al. (1979) reported a peculiar time dependence during upstream particle events: lower energy particles reach their equilibrium intensity level earlier than higher energy particles. When the magnetic field changes from the no bow shock connection case to bow shock connection, upstream protons of 30 keV appear within a few minutes and reach then a constant intensity level. Protons of 130 keV either do not reach a plateau profile as a function of time at all or with a delay of ~ 30-40 min. These dispersion effects have been explained in terms of a time-dependent Fermi acceleration process in the following manner: let us assume that the upstream field turns from a nonconnected situation into a nearly solar wind flow aligned situation (radial field). At the satellite position the intensities will build up in the time-dependent acceleration process with an energy dependent time constant τ. Scholer et al. (1980a) have calculated from the observed time dispersion at various energies the diffusion coefficient and its energy dependence. The mean free path at 30 keV is 4 R_E and the diffusion coefficient depends about linearly on energy. The field line connection time has therefore to be considerably larger in order to observe diffuse upstream particles at higher energies.

Discrimination between protons and alpha particles is essential in order to obtain differential intensity spectra of diffuse ions in the higher energy range. Ipavich et al. (1981) have shown that diffuse ions exhibit above ~ 15 keV spectra which can be very well represented by exponentials in energy. Figure 6 shows proton, alpha particle and heavy ion spectra averaged over the plateau phase of an upstream event (Ipavich et al., 1981) in a log versus lin representation. Note that the least squares fit to the H, He, and heavy ion spectra have the same slope, i.e. the abundance ratios are constant when evaluated at equal energy per charge.

Recently, Wibberenz et al. (1985) have performed a detailed analysis of the relation between field line connection time, the occurrence of upstream ions, and the spectral parameter (e-folding energy) of the differential intensity spectrum. They found that the hardest spectra require in general connection times above 40 min. Although the spacecraft may be magnetically connected with the bow shock all the time (positive connection time) the energetic proton intensity is nevertheless controlled by the magnitude of the connection time. This is according to Wibberenz et al. a strong argument against a magnetospheric origin of the upstream particle population during these events.

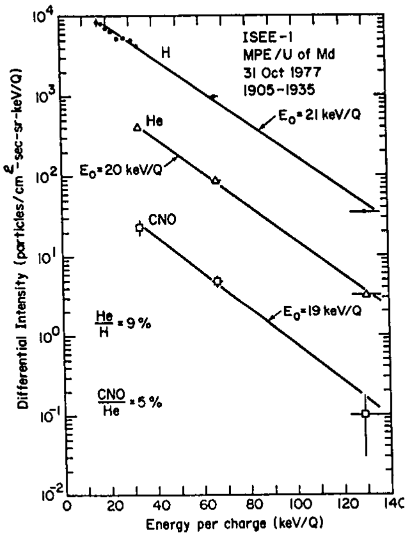

Fig. 6 Proton, alpha particle and heavy ion spectra (C, N, O) spectra during an upstream diffuse particle event (Ipavich et al., 1981).

We should like to make a few comments on the contribution of magnetospheric energetic particles to the upstream ions. The magnetosphere is known to be a large reservoir of energetic ions and electrons and these particles may escape occasionally upstream (e.g. Sarris et al., 1976b, 1978). Scholer et al. (1981) have tried to separate the magnetospheric population from the bow shock accelerated population by analyzing energetic electrons. They found two types of upstream proton events: one group is accompanied by energetic electrons and extends up to energies of 300 keV, a second group is not accompanied by energetic electrons and can be represented very well by exponential energy spectra. Scholer et al. suggested that the first group is of magnetospheric origin and the second group is due to bow shock acceleration. Recently, Anagnostopoulos et al. (1985) have questioned the interpretation of upstream ions above $\sim$ 50 keV in terms of diffusive shock acceleration. They claim that many, if not all upstream ion events above this energy are of magnetospheric origin. This has renewed interest in the topic of upstream events and a careful reevaluation of this topic appears necessary.

5. Theory of Shock Acceleration. The first analytical treatment of diffusive shock acceleration has been given by Fisk (1971) and has been developed in considerable detail by Krimsky (1977), Axford et al. (1977), Bell (1978 a, b) and Blandford and Ostriker (1978). In this model it is assumed that particles are scattered approximately elastically in the frame of the plasma. The elastic scattering is due to small-angle pitch angle scattering by hydromagnetic waves that convect approximately with the local flow speed. The particles which are scattered back toward the bow shock in the upstream medium can gain considerable energy in the shock frame. The particles are possibly reflected back from the shock front or are scattered back by downstream waves so that particles can reencounter the shock many times. This scenario does not describe how an initial reflection of a fraction of the solar wind ions incident on the shock gets the acceleration process started. In the simple case of a plane shock and monoenergetic injection at some momentum p_o the distribution function is in the steady state at the shock given by a power law for $p > p_o$, i.e. $f \propto E^{-\gamma}$ where γ related to is the velocity difference between the upstream and downstream scattering centers. If the initial spectrum is softer than what the shock would produce for monoenergetic injection, than the spectrum near the shock is altered to the "shock" spectrum at higher energies. On the other hand, if the initial spectrum is flatter than the "shock" spectrum, the initial power law is preserved at high intensities but the intensities are shifted upward (see, e.g. Axford, 1981).

The spatial dependence of the distribution function upstream along the magnetic field is essentially given by an exponential with an e-folding distance L, $L = \varkappa_{\parallel}/V_1$. Since $\varkappa_{\parallel}$ in general increases with energy the e-folding distance of the phase space density depends on energy as well. Thus, the distribution function is a power law only at the shock and in the down-stream medium. Note that in the steady state and for infinite plane shocks the form and the absolute value of the distribution function is independent of the diffusion coefficient. The mean free path only determines how fast the steady state is reached. Further ahead of the shock the distribution function does depend on the form of the diffusion coefficient and tends to the peaked because the intensity of low energy particles falls off faster with distance upstream than high energy particles. As outlined in the first section, spectra of corotating events are not power laws as predicted by the steady state diffusive acceleration model at planar shocks, but close to exponentials in velocity. Fisk and Lee (1980) have included the adiabatic deceleration term due to the radially expanding solar wind. They were able to show that upstream diffusion of the shock accelerated particles against the radially expanding solar wind leads to a steepening of the spectra with increasing energy. The leading dependence of the distribution function on particle velocity is an exponential which is independent of particle species. Furthermore their theory predicts a steeper spectrum at the forward shock than at the reverse shock, consistent with the observations (Scholer et al., 1980b).

The exponential spectral form of ion events upstream of the bow shock is also at variance with the prediction of diffusive shock acceleration at planar shocks in the steady state. Scholer et al. (1980a) have suggested that the steepening of the spectrum could be due to the limitation of the upstream wave field to some distance close to the shock and have introduced the concept of a free escape boundary. Such a free escape boundary does, of course, not really exist in nature; it is simply a means to conveniently describe the loss of particles out of the system. An analytical solution for this scenario within the limits of diffusion theory has been given by Lee et al. (1981) and Forman (1981). Ellison (1981) and Terasawa (1981) also used a free escape upstream in their numerical models.

Any process where the loss increase with energy results in a steepening of the spectra. Eichler (1981), in contrast to upstream escape, proposed as a loss process diffusive transport normal to the magnetic field and lateral free escape along field lines not connected to the bow shock. Eichler (1981) found that in addition to the spectra being close to the observed exponential form they are functions of energy per charge only, independent of the assumed mass, charge and energy dependence of the parallel diffusion coefficient.

A theory for the coupled behaviour of the hydromagnetic waves and diffuse ions that result when the magnetic field is nearly parallel to the solar wind has been presented by Lee (1982). The diffuse ions stream relative to the solar wind in the upstream direction with a velocity greater than the solar wind velocity and are therefore subject to the hydromagnetic streaming instability, the threshold of which is the Alfvén speed. This results in the growth of the hydromagnetic waves that propagate upstream, which in turn scatter the particles toward isotropy thus reducing the growth rate. At the same time waves propagating toward the shock are damped. The growth or damping rate is determined by the pitch angle anisotropy of the distribution function. Assuming an interplanetary wave activity far upstream with the waves travelling toward, the bow shock, perpendicular diffusion is required to yield other than power law spectra at the shock. For this case Lee (1982) determined uniquely the distribution function and the power spectral density as a function of distance from the shock.

A self-consistent theory for the excitation of hydromagnetic waves and the diffusive acceleration at travelling interplanetary shocks has also been given by Lee (1983). The interplanetary shock is assumed to be planar so that cross-field diffusion does not have to be considered. Since the distribution function decreases with distance upstream of the shock, the waves propagating away from the shock front in the frame of the solar wind are unstable. Interplanetary hydromagnetic waves in the spacecraft frame are observed to propagate predominantly away from the sun. Thus, the streaming anisotropy leads only to wave growth of the "background" outward travelling waves. This, together with the boundary condition at the shock and the condition that the distribution function is zero at large distances from the shock, allows the unique determination of the differential wave intensity spectrum and of the ion omnidirectional distribution function as a function of distance upstream. A test of this quasi-linear theory has recently been performed for a specific quasi-parallel interplanetary shock by the so-called "November 11-12 shock-collaboration group" under the lead of C.F. Kennel and will be reported in section 6.

We will briefly discuss the shock drift mechanism which is presumably responsible for the shock spike events. In this so-called V x B mechanism particles gain energy in a single shock encounter by drifting in the inhomogeneous magnetic field at the shock front parallel to the V x B electric field. This mechanism was first proposed for acceleration of solar wind ions at the earth's bow shock by Sonnerup (1969). The most detailed theoretical analysis of this process has been given by Decker (1982, 1983). He calculated intensity enhancements, energy spectra, and pitch angle distributions of an initial or ambient particle distribution after a single shock encounter. The intensity enhancement and the pitch angle distribution depends strongly on the ratio of a particle's initial energy T and the energy T_0 defined by the Hoffman-Teller velocity V_{HT}. (V_{HT} is the velocity of a system moving parallel to the shock front, so that the flow upstream and downstream is field aligned). Ions with $T/T_0 \gtrsim 1$ stream upstream away from the shock (in the plasma frame), at $T/T_0 \gg 1$ the effect of the loss cone leads to an intensity minimum parallel to the field. In the downstream medium ions with $T/T_0 < 1$ stream towards the shock (in the plasma frame), ions with $T/T_0 \gg 1$ exhibit a pancake-like distribution, i.e. the intensity is enhanced at 90^o with respect to the magnetic field. Sanderson et al. (1984) have compared these predictions with distributions measured in shock spike events at quasi-perpendicular shocks. They found during these events large negative values of the downstream second harmonic anisotropy. This is the most recognisable feature of the drift acceleration model, and is due to the ions gyrating around the field at pitch angles of $\sim 90^o$.

As pointed out by Lee (1984) the distinction between the shock drift and the diffusive acceleration rests not on basic physics but on whether one or many encounters is appropriate to a particular particle population. In general a particle gains energy by <u>both</u> compression and drift parallel to the motional electric field, although the separtion of the energy gain into compressional and drift contributions is frame-dependent (in the Hoffman-Teller frame, for example, the drift contribution vanishes). In a single encounter of a particle with an oblique shock with no scattering there is, of course, no compressional energy gain. When comparing the efficiency and the relative merits of quasi-parallel and quasi-perpendicular shocks, respectively, as particle accelerators, it should be noted that the relevant diffusion coefficient in the diffusive shock acceleration theory is that in the shock normal direction, κ_n. Since $\kappa_n \approx \kappa_\parallel \cos^2 \Theta_{Bn}$, where $\kappa_\parallel$ is the diffusion coefficient parallel to the magnetic field, it is trivial that as long as the steady state is not reached quasi-perpendicular shocks are more "efficient" accelerators. For a shock with $\Theta_{Bn} = 87.5^o$ as reported by Krimigis and Sarris (SH 1.5-4), the effective diffusion coefficient is reduced by 2-3 orders of magnitude.

<u>6. Test of the Quasi-linear Theory.</u> Kennel et al. (1985) have recently performed a detailed test of the quasi-linear theory of diffusive acceleration as predicted by Lee (1983), using ISEE-3 measurements of the November 12, 1978 quasiparallel shock. The quasilinear theory makes ten specific predictions for the particle and wave signatures. We will now briefly report on the result of the Kennel et al. study.

1. The energetic ions at the shock should have a power law velocity distribution. This has been observed to be the case with the power law index, β, between 4.20 and 4.25 (Scholer et al., 1983, Van Nes et al., 1984).

2. The index is related to the upstream and downstream velocity of the scattering centers. Kennel et al. found that when correcting the upstream and downstream plasma velocities for the Alfvén velocity the predicted index is 4.2 when neglecting the Alfvén velocity an index of 4.7 is predicted (in substantial disagreement with the observations).

3. The upstream scale length (e-folding distance) should increase with energy according to a power law. The power law index α is related to the index β of the power law distribution function via $\alpha = (\beta - 3)/2$. The parameter α derived from the measured scalelengths is in excellent agreement with this relation.

4. The absolute magnitude of the scalelength should depend inversely upon the partial number density of energetic protons at the shock. From the measured number density the scalelength is correctly predicted.

5. Upstream of the shock the parallel anisotropy should be positive in the solar wind frame (away from the shock) and constant. The measurements show a constant anisotropy of ~ 0.3 in the upstream region and a zero anisotropy immediately downstream of the shock.

6. The phase and group velocity of the waves should be directed upstream along the magnetic field. This cannot be tested with a single spacecraft. The wave spectrum is however weakly polarized, with a roughly equal mixture of right-hand and left-hand waves, as prescribed by the quasilinear theory.

7. The scalelength of the magnetic energy density of the upstream waves should be equal to the scale length of the protons in cyclotron resonance with them. The scalelength of the trace amplitude between 0.02 and 0.06 Hz indeed corresponds to the scalelength of ~ 40 keV protons.

8. The total wave magnetic energy density integrated over the spectrum of resonant waves is predicted to be proportional to the total energy density of the upstream ions. Extrapolating the measured power law of the distribution function down to 3 keV the quasilinear estimate agrees indeed with the measured normalized trace amplitude of the waves.

9. The magnetic field power spectrum of the self-excited waves should increase towards lower frequencies according to a power law with a spectral exponent $\delta = 6 - \beta$. However, the observations show a flat or even peaked spectrum in the respective frequency range.

10. There should be no wave excitation at frequencies larger than the resonance frequency of a proton whose component of parallel velocity in the shock normal direction is zero in the shock frame. This frequency is about 0.1 Hz. However, the spectral density above 0.1 Hz was several hundred times larger than that in the solar wind.

This detailed investigation shows that the quasi-linear theory successfully predicts numerous observations at this particular quasi-parallel shock. The wave power spectrum is related to the protons via the resonance condition which invokes the particle's parallel velocity. Since the theory by Lee (1983) makes approximations that essentially loose the pitch-angle dependence of the particle distribution it is not unexpected that this theory gives not better agreement with the observed wave spectrum.

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