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Simultaneous Observations of Energetic Protons Close to the Bow Shock and Far Upstream*

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Abstract. We have investigated four energetic proton events (30 keV–75 keV) upstream of the earth's bow shock with two identical experiments of the Max-Planck-Institut/University of Maryland on satellites ISEE-1 and ISEE-3. Close to the bow shock the particle distribution is more or less isotropic and indicates relatively strong scattering of these particles in the upstream wave field. At ISEE-3 between 100 and 200 R_E upstream from the earth's bow shock, the particles move essentially scatter-free from the general bow shock direction. The proton differential intensity at ISEE-3 is a factor of about 4–15 less than at ISEE-1 at 30 keV. The spectra at ISEE-1 are steeper than the spectra at ISEE-3. Flux ratios and spectra are discussed in terms of a first order Fermi acceleration model with a diffusion coefficient increasing approximately linearly with energy and a free escape boundary at some distance upstream.

Key words: Earth's bow shock – Upstream particles – Shock acceleration

Introduction

Early observations of energetic particles upstream of the earth's bow shock have been reported by Asbridge et al. (1968) and Lin et al. (1974). The ISEE-1 and -2 satellites with their highly eccentric orbits and the ISEE-3 satellite in a halo orbit around the libration point have opened a new era in the study of bow shock associated particle and wave phenomena. The ions upstream of the bow shock exist in two distinctly different components (Gosling et al. 1978), the socalled reflected and diffuse components. The reflected component is essentially a beam directed outward from the shock along interplanetary field lines, whereas the diffuse ions are characterized by relatively flat energy spectra and broad angular distributions. The reflected ion beam typically has energies of several keV and can be explained by an acceleration of solar wind ions in terms of a displacement along the interplanetary electric field during particle reflection at the bow shock (Paschmann et al. 1980). One rare occasions ion beams up to energies of ~65 keV have been observed (Scholer et al. in press 1981). Diffuse upstream ion events usually last up to several hours and can extend in energy up to least 100 keV (Ipavich et al. 1979; Scholer et al. 1979). Ipavich et al. (1981) have shown that the spectra of protons and alpha particles in these events are generally well described as exponentials in energy per charge and that the ratio of the fluxes of the two species is constant as a function of energy. In a statistical analysis Scholer et al. (1980a) have shown that the rate of occurrence of upstream diffuse events increases with decreasing angle between magnetic field and radial direction (i.e., sun-earth direction). They concluded that the field line connection time with the bow shock is the determining factor for the occurrence of diffuse upstream ions, and they suggested that these ions are accelerated by a first order Fermi mechanism at the shock. Such an acceleration process has been discussed in detail by Fisk (1971), Scholer and Morfill (1975), Axford et al. (1977), Bell (1978a, b), and Blandford and Ostriker (1978).

Simultaneous measurements at ISEE-1 close to the bow shock and at ISEE-3 far upstream have shown that, whereas the particle distribution close to the shock is more or less isotropic, the particles far upstream are moving essentially scatter free (Scholer et al. 1980b). Thus, the turbulent magnetic waves responsible for particle scattering have to be limited to some region close to the bow shock. Beyond some distance L particle transport becomes scatter free and the particles can escape freely into the far upstream medium. Sanderson et al. (in press 1981) and Anderson (in press 1981) have studied detailed pitch angle distributions at ISEE-3. They reported, in addition to the sunward streaming along the interplanetary magnetic field, pitch angle asymmetries due to density gradients and due to the electric field induced by the motion of the interplanetary magnetic field.

In this paper we study in detail four upstream particle events which were simultaneously observed by ISEE-1 and ISEE-3. In particular, we make a comparison between the absolute flux values $\sim 200 R_E$ (earth radii) from the bow shock and flux values several R_E in front of the bow shock at two different energies and interpret the results in terms of a model invoking a first order Fermi mechanism at the shock and a free escape boundary somewhere upstream.

The observations were obtained with two identical instruments, the *Ultra-Low-Energy-Charge-Analyzer* (ULECA) of the Max-Planck-Institut/University of Maryland sensor system on ISEE-1 and ISEE-3. A detailed description of the instrument may be found in Hovestadt et al. (1978).

Observations

In the following, we discuss four upstream particle events for which we have simultaneous measurements at ISEE-1 and -3. The positions of the two spacecraft during these events are shown in Fig. 1 in a projection onto the solar-ecliptic plane. Figure 2

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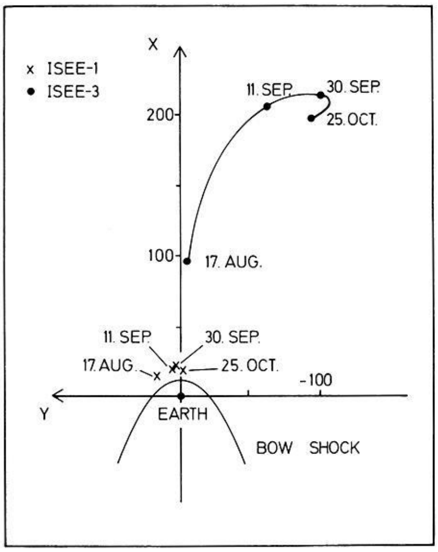

Fig. 1. The spatial location of the ISEE-1 and -3 spacecraft at times of the upstream particle events discussed in the paper, in the solar ecliptic plane

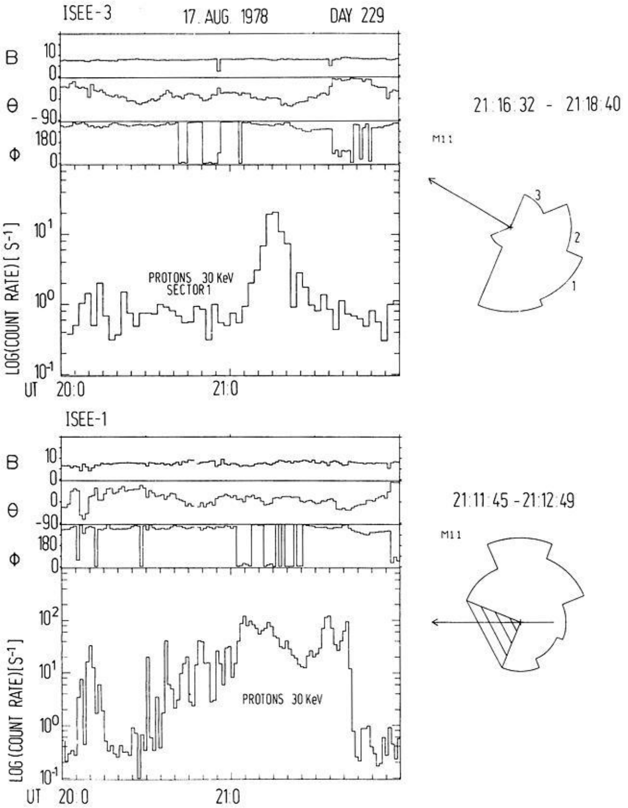

Fig. 2. Magnetic field and particle data during the 17 August 1978 event. *Top left:* magnetic field in gammas, θ and Φ component in solar-ecliptic coordinates (*upper three panels*) and intensity-time profile of energetic particles at ISEE-3; *top right*: typical anisotropy measurement during the upstream particle burst. *Lower left:* magnetic field and particle data at ISEE-1 during same time period; *lower right:* typical anisotropy measurement observed at ISEE-1. The sun is to the left, the *arrow* indicates the projection of the magnetic field onto the ecliptic

shows, on the left side, a 2 h interval of particle and magnetic field data on 17 August 1978. The upper left part of Fig. 2 shows, in the upper three panels, the magnetic field magnitude (in gammas) and the θ and Φ components in solarecliptic coordinates as measured on ISEE-3. The next panel shows the 30 keV proton count rate. The lower left part of Fig. 2 shows the same data for ISEE-1. To the upper and lower right side of Fig. 2 we show typical examples of anisotropy measurements during this time period at the two satellites; shown is the counting rate (on a linear scale) in 8 sectors which are scanning in the ecliptic plane (the sun is to the left of the figure). Due to the fan-like aperture the fluxes are integrated over an angular range of ±30° out of the ecliptic. The time-intensity profile at ISEE-3 is the intensity in sector 1 (for sector numbering see the anisotropy samples). For ISEE-1 we show the spin averaged count rate.

Since several rate channels of the ULECA sensor on ISEE-1 are sensitive to sunlight, depending on the orientation of the spin axis with respect to the spacecraft-sun line, the sun sector (and sometimes the following sector) has to be eliminated as indicated by the shaded portion. Also shown is the magnetic field direction in the ecliptic plane. At ISEE-3 particles arrive anti-parallel to the field from the bow shock direction with pitch angles down to 90°, while at ISEE-1 the distribution is more or less isotropic. This has already been observed during other events by Scholer et al. (1980b) and by Sanderson et al. (in press 1981) and Anderson (in press 1981).

In comparing absolute fluxes and spectra at the two spacecraft we have to consider an important point. Charged particles moving upstream are subject to the electric field induced by the motion of the interplanetary magnetic field. The resulting drift perpendicular to the magnetic field leads for each particle velocity parallel to the magnetic field, $v_{\parallel}$, to a foreshock boundary; upstream of this boundary no particles with velocity $v_{\parallel}$ can be observed. Close to the field line tangent to the bow shock particles are therefore arranged in the form of sheets according to their parallel velocity (Anderson, in press 1981). However, assuming that acceleration takes place everywhere at the bow shock and not only close to the point of tangency as assumed by Anderson (in press 1981) we will have, at any point not too close to the line of tangency, a superposition of particles with different velocities $v_{\parallel}$. (Actually, as shown by Scholer et al. (1980a) diffuse ions are not accelerated close to the point of tangency of a field line with the bow shock, but reach their steady state after a relatively long (~60 min) field line connection time).

Spectra taken well within an event and not at the event onset are therfore most likely to be representative of the spectra at the distance from the bow shock where the particles escape freely into the upstream medium. At the event onset, on the other hand, one might observe high energy particles first and low energy particles later, as the sunward side of the ion sheets moves over the spacecraft. There is also an earthward spatial limitation of the particle distribution; as this boundary sweeps over the spacecraft one will observe anisotropies of the particle distribution perpendicular to the magnetic field due to the effect of a density gradient perpendicular to the magnetic field.

Sanderson et al. (in press 1981) report gradient anisotropies at the onset as well as at the end of an upstream particle event observed at ISEE-3. Note, however, that these authors present data from ISEE-3 only. Observations of particle bursts far upstream from the bow shock cannot alone reveal whether these particles are bow shock associated or of magnetospheric origin.

Figure 3 shows differential spectra during the 17 August 1978 event at both spacecraft. We have taken, at both spacecraft, the

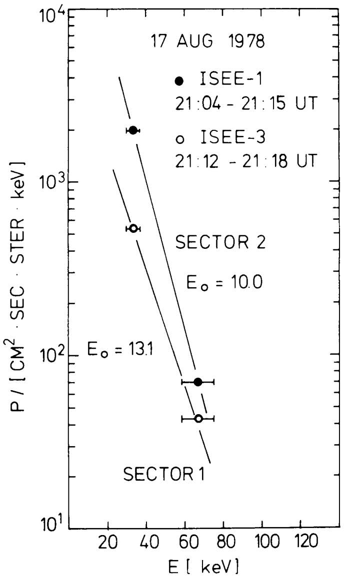

Fig. 3. Two-point spectra (of the flux in the sector containing the magnetic field) during the 17 August 1978 event as observed on ISEE-1 and ISEE-3. The flux is plotted linearly vs energy (in cm^2 s.sr.keV)$^{-1}$; E_0 the *e*-folding energy assuming a representation as an exponential in energy

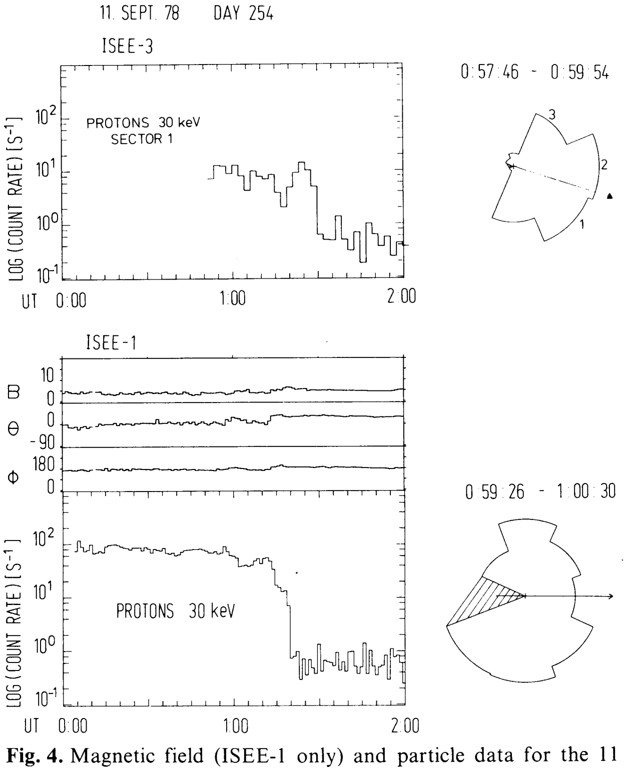

Fig. 4. Magnetic field (ISEE-1 only) and particle data for the 11 September 1978 upstream event

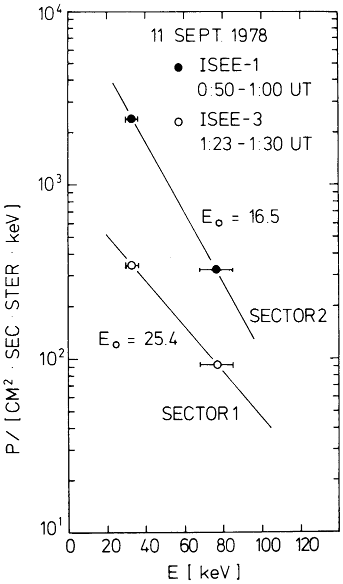

Fig. 5. Spectra during the 11 September 1978 event

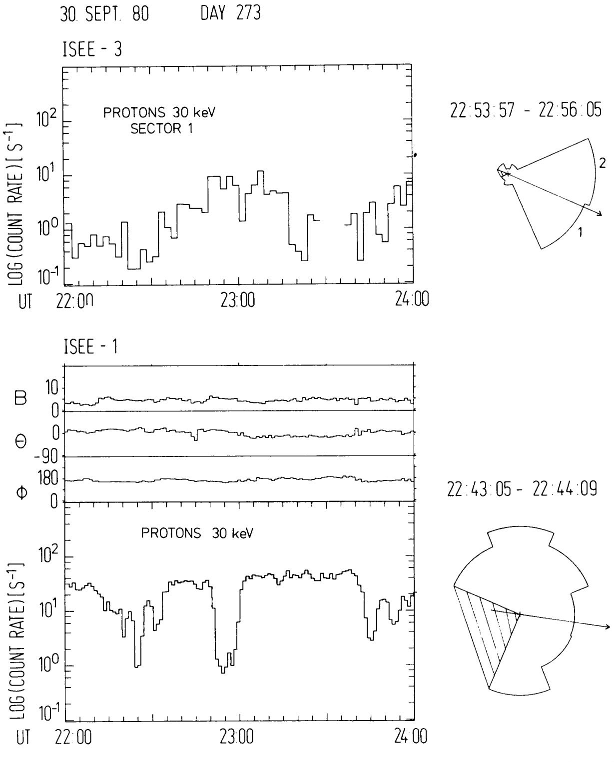

Fig. 6. Magnetic field (ISEE-1 only) and particle data for the 30 September 1978 upstream event

intensity in the sector containing the magnetic field direction (flux of particles streaming away from the bow shock along the interplanetary magnetic field). The spectra are plotted linearly against energy. It has been shown by Ipavich et al. (in press 1981) in a statistical analysis of upstream events measured at ISEE-1 that the spectra can be represented reasonably well by exponentials in energy over the energy range 30–160 keV. Therefore we have fitted exponentials in energy through the two point spectra obtained in this analysis (the fluxes at higher energies, i.e., at 120–160 keV, at ISEE-3 for these events are always at background level and cannot be used in the spectral representation). Also given in Fig. 3 is the *e*-folding energy E_0 of the two point spectra. As can be seen from Fig. 3 the spectrum at ISEE-1 is steeper ($E_0 = 10$) than the ISEE-3 spectrum ($E_0 = 13.1$). Flux ratios between

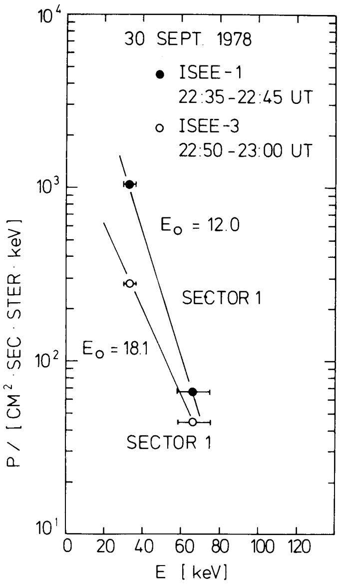

Fig. 7. Spectra during the 30 September 1978 event

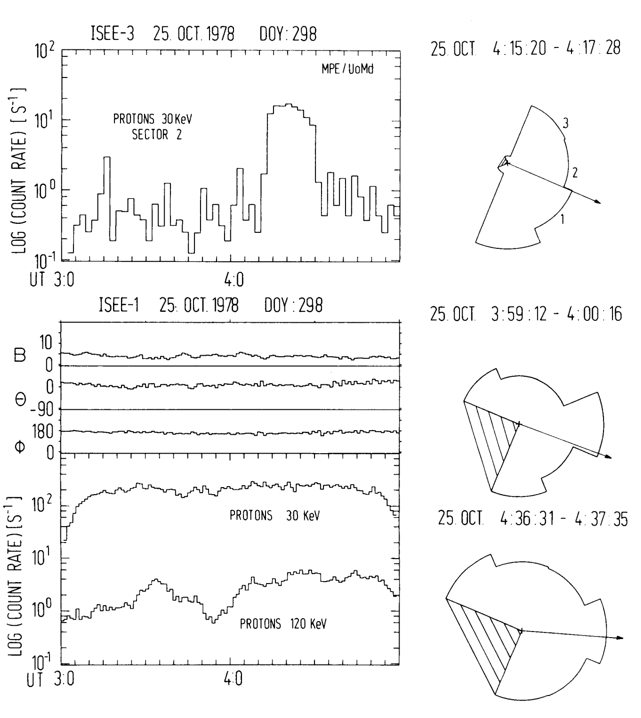

Fig. 8. Magnetic field (ISEE-1 only) and particle data for the 25 October 1978 upstream event

ISEE-1 and ISEE-3 are 3.7 at ~30 keV and 1.6 at ~65 keV, respectively. When comparing spectra between ISEE-1 and ISEE-3 it should be noted that the intensities at both satellites are time variable and that intensities are different in different sectors. Thus a comparison as made here has, of course, to be considered with caution.

Figure 4 shows magnetic field (ISEE-1 only) and particle data during an upstream event on 11 September 1978 in the same representation as in Fig. 2. Figure 5 shows corresponding spectra. The spectra are somewhat harder (E_0 = 16.5 and 25.4, respectively), the flux ratios are 7.0 and 3.5 at ~30 keV and ~65 kev, respectively.

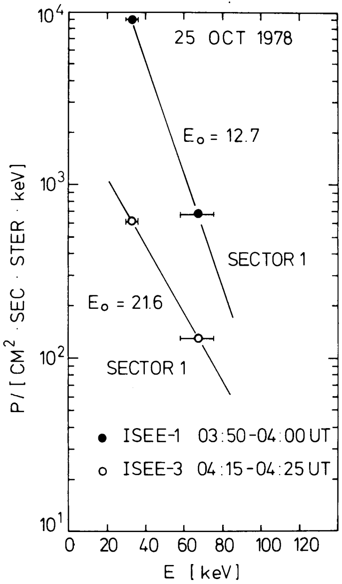

Fig. 9. Spectra during the 25 October 1978 event

Figure 6 shows an event on 30 September 1978 and Fig. 7 shows the corresponding spectra. We have always taken the spectra 10–20 min earlier at ISEE-1 than at ISEE-3, allowing for a propagation time of protons parallel to the field between the region close to the shock and ISEE-3 at ~200 R_E. The flux ratios of upstream moving particles during the 30 September event are 3.8 and 1.5 at ~30 keV and ~65 keV, respectively. Finally, Fig. 8 shows magnetic field and particle data for the 25 October 1978 event, which has been previously published in Scholer et al. (1980c). The spectra in Fig. 9 show that there are large flux changes between the two satellites, flux ratios being 14.8 and 5.2 at ~30 keV and ~65 keV, repectively.

At ISEE-1 there is a flux decrease at higher energies (~120 keV) from ~3:50–4:00 UT. If we had chosen the time interval from 4:05–4:15 UT for the spectral representation at ISEE-1 the flux ratios would have been ~14.5 and ~10 at ~30 keV and ~65 keV, respectively; the *e*-folding energy during this time interval is ~16.8 keV.

Discussion and Interpretation

We have presented simultaneous observations of upstream energetic protons close to the bow shock at ISEE-1 and far upstream at ISEE-3 during four different events. The results of this investigation are:

1. The proton angular distributions are more or less isotropic at ISEE-1 whereas at ISEE-3 no particles are seen to return from upstream to the spacecraft. Scattering of particles at ISEE-3 is therefore weak and particles move essentially scatter free.
2. Comparison of absolute flux values shows that there is a flux decrease between ISEE-1 and ISEE-3 by a factor which varies between ~4 and ~15 at ~30 keV.
3. Spectra close to the bow shock are always steeper than spectra far upstream. At ~65 keV the flux is reduced only by ~1.6 to ~5.
4. It seems that the flux decrease is larger if the spectra close to the bow shock are harder (11 September event) and less if the spectra close to the shock are steeper (e.g., 17 August event). This is clearly based on only a few events and is not conclusive.

In Scholer et al. (1980a) we have argued that diffuse upstream particles at energies $\gtrsim 30$ keV can probably be explained in terms of a first order Fermi mechanism at the bow shock. In an infinite medium such an acceleration mechanism predicts a power law spectrum close to the shock, whereas the observations show that the spectrum is very close to an exponential in energy. We have therefore suggested that the spatial limitation of the scattering region upstream of the shock together with a mean free path increasing with energy leads to a spectral form similar to an exponential in energy. From intensity-time profiles at different energies Scholer et al. (1980a) have indeed derived a diffusion coefficient, κ, proportional to energy, more specifically to energy per charge, $\kappa \propto E/Q$.

Recently, Lee et al. (in press 1981) have solved the stationary equations for first order Fermi acceleration at a plane shock under the boundary condition that, at some distance L upstream, the omnidirectional distribution function, f, is zero. They find that in the limit $V_S L/\kappa \ll 1$ (V_S = upstream plasma velocity relative to the shock) and under the assumption $\kappa \propto E$ the energy dependence of f is given by an exponential in energy. Assuming f to be zero at some distance $x = L$ is not critical for calculating spectra close to the shock, but in the frame work of such a model we can, of course, not compare spectra close to the shock and at or beyond the distance L. If we want to compare spectra close to the shock and far upstream we have to invoke a two-component model for the particle populations moving in the $+x$ and $-x$ directions, respectively, as proposed by Terasawa (in press 1981). With U^+ and U^- as the corresponding differential number densities, the diffusion-convection equations in the rest frame of the shock read:

$$\begin{aligned}(\bar{v} - V_S)\frac{\partial}{\partial x}U^+ &= \frac{1}{\tau}(U^- - U^+)\\ (\bar{v} + V_S)\frac{\partial}{\partial x}U^- &= \frac{1}{\tau}(U^+ - U^-)\end{aligned} \tag{1}$$

where τ is the characteristic scattering time, $\bar{v}$ is the pitch angle averaged velocity in the rest frame of the plasma: $\bar{v} \approx v/2$; $\kappa \approx \frac{1}{2}\tau\bar{v}^2$. Assuming at $x = L$ the boundary condition $U^-(x = L) = 0$ the solution to (1) is (Terasawa, in press 1981):

$$\begin{aligned}U^+ &= g(\bar{v})\left[\exp(-V_S x/\kappa) - \frac{\bar{v} - V_S}{\bar{v} + V_S}\exp(-V_S L/\kappa)\right]\\ U^- &= g(\bar{v})\frac{\bar{v} - V_S}{\bar{v} + V_S}\left[\exp(-V_S x/\kappa) - \exp(-V_S L/\kappa)\right]\end{aligned} \tag{2}$$

where $g(\bar{v})$ is a function of velocity only and has to be determined by the boundary condition at the shock, $x = 0$.

Figure 10 shows the ratio $\chi = U^+(x = L)/U^+(x = \mathrm{o})$, as obtained from (2) for two different energies and a solar wind velocity of 400 km/s vs the parameter $V_S L/\kappa$. Assuming $\kappa \propto E$ the value of $V_S L/\kappa$ is, at 60 keV only half the value of $V_S L/\kappa$ at 30 keV and this results, according to Fig. 10, in a larger value χ (60 keV). This predicts a flattening of the spectrum between ISEE-1 and ISEE-3, which is indeed observed during all four events investigated. Variability in the flux ratios between ISEE-1 and ISEE-3 from one event to the next is, according to this model, due to changes in the parameter $V_S L/\kappa$. From the measured flux decreases we obtain values of $V_S L/\kappa$ at 30 keV between ~ 1 and ~ 2. This is, of course, only true if there is no further loss between the region of free escape and the point of observation far upstream.

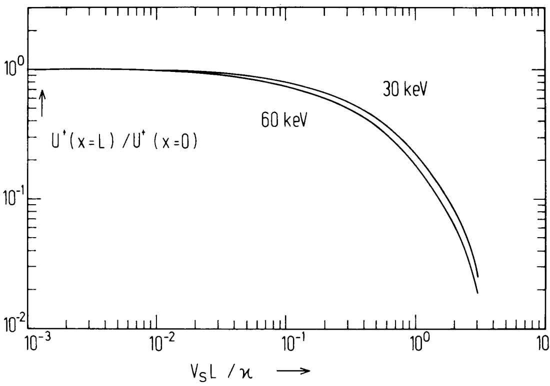

Fig. 10. Ratio of flux of particles flowing upstream at the free escape boundary ($x = L$) to flux of particles flowing upstream at the shock ($x = \mathrm{O}$) vs $V_S L/\kappa$

The measured difference in the flux ratio between ISEE-1 and ISEE-3 at the two different energies, ~ 30 keV and ~ 60 keV, can only be explained if the diffusion coefficient increases with energy at least according to $\kappa \propto E$ (assuming L to be independent of energy). Note, that this results is independent of the knowledge of the spectral shape, i.e., the function $g(\bar{v})$, and is based only on ratios near the shock and beyond L at different energies. This is consistent with our earlier result in Scholer et al. (1980a), where we derived a linear dependence of κ on E from the intensity-time profiles. However, the data are also not inconsistent with an energy dependence of κ such as $\kappa \propto E^{1.5}$ as required by Terasawa (in press 1981) in his acceleration model, where the shock is considered to be a partial reflector of particles.

As mentioned earlier, Lee et al. (in press 1981) have derived the spectrum of the accelerated particles by assuming that, at the shock, the product of particle differential streaming with the cross sectional area of a flux tube across the shock is conserved. In the limit $V_S L/\kappa << 1$ and assuming $\kappa \propto v^2$ the distribution function, f, at the shock is an exponential in velocity squared. From the absolute flux comparison we have seen that $V_S L/\kappa$ is of the order of 1. It can, however, be shown that even for values $V_S L/\kappa \sim 1$ the distribution function can still be fitted very well over a limited energy range, say from 30–160 keV, by an exponential in energy and that values of $V_S L/\kappa_{30}$ between 1 and 2 ($\kappa_{30} = \kappa$ at 30 keV) will result in e-folding energies, E_0, between ~ 10 and 20. The e-folding energy increases with $V_S L/\kappa_{30}$, larger values of $V_S L/\kappa_{30}$ lead, according to Fig. 10, to larger flux differences between $x = 0$ and $x = L$ which is consistent with the observations of e-folding energies close to the shock, as presented in this paper.

In summary, we have studied four upstream particle events where simultaneous data exist close to the bow shock from ISEE-1 and far upstream from ISEE-3. The flux (in the sector containing the magnetic field) far upstream is lower by a factor which ranges from 4 to 15 at 30 keV for the four events. The spectra far upstream are harder than the spectra close to the shock. The spectra and flux differences can be understood in a model where particles are accelerated by a first order Fermi mechanism at the shock. The scattering has to be limited to some region close to the shock, the distance from the shock is of the order of κ/V_S with κ as the diffusion coefficient at ~ 30 keV and V_S as the solar wind velocity. The diffusion coefficient used in this model has to increase approximately linearly with energy.

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