# SPATIAL DEPENDENCE OF THE LOCAL DIFFUSION COEFFICIENT MEASURED UPSTREAM OF THE NOVEMBER 12, 1978 INTERPLANETARY TRAVELING SHOCK

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1. Introduction. Characteristics of suprathermal particles accelerated by quasi-parallel interplanetary traveling shocks have been generally explained in terms of a first order Fermi mechanism (e.g. see review in ref. 7). Such models require diffusive scattering of particles upstream of the shock. This scattering is characterized by a local diffusion coefficient, $\kappa$, which is determined by the local power density of waves in the upstream region as described by Lee (7). A number of studies have investigated the behavior of $\kappa$ of $\lesssim 1$ MeV upstream ions close to interplanetary shocks. Scholer et al. (8) have used results of first order Fermi shock acceleration theory (e.g. ref. 1) to derive the diffusion coefficient and its energy dependence from the measured gradient of the upstream particle intensity. Van Nes et al. (9), using the same approach, obtained the spatial and energy dependence of $\kappa$ for 3 interplanetary shocks over a more extended energy and distance range. Klecker et al. (6) deduced the spatial dependence of $\kappa$ in the upstream region for 30 and 130 keV protons from the measured first-order anisotropies and intensity gradients.

In this paper we examine the dependence of the diffusion coefficient of suprathermal upstream protons on distance from the November 12, 1978 interplanetary traveling shock using a different approach. Unlike previous studies our method, which is based on measurements of particle streaming and intensity gradients, does not rely on predictions of shock acceleration theories or require first-order expansions. We have chosen to examine the local spatial variations of $\kappa$ upstream of the November 12, 1978 shock because the characteristics of this quasi-parallel shock have been extensively studied (e.g. ref. 5), and also because of its favorable geometry (i.e. B field nearly radial). The initial results of this study have been reported by Gloeckler et al. (3).

2. Instrumentation and Method of Analysis. For this study we use the counting rate data from the University of Maryland/Max-Planck-Institut-Garching ULECA sensor (see ref. 4 for details) on ISEE-3 which was placed in a halo orbit at a radial distance of ~230 $R_E$ upstream of the earth. Of relevance to the present discussion are the capabilities of the electrostatic deflection vs energy ULECA sensor to reliably separate protons from alpha particles and to determine their differential intensities in three energy bands centered on energies $\bar{E}$ of 33, 66 and 132 keV/e, and respective band widths $\Delta E/\bar{E}$ of 20, 27 and 37%. The sensor has a 60° fan-like acceptance aperature with its wide angle in a plane perpendicular to the ecliptic. The three proton counting rates are available every 128 sec in each of eight 45° sectors of the ecliptic plane.

For the present analysis we use the 33 and 66 keV sectored proton counting rate data to derive the proton distribution function, f, in the

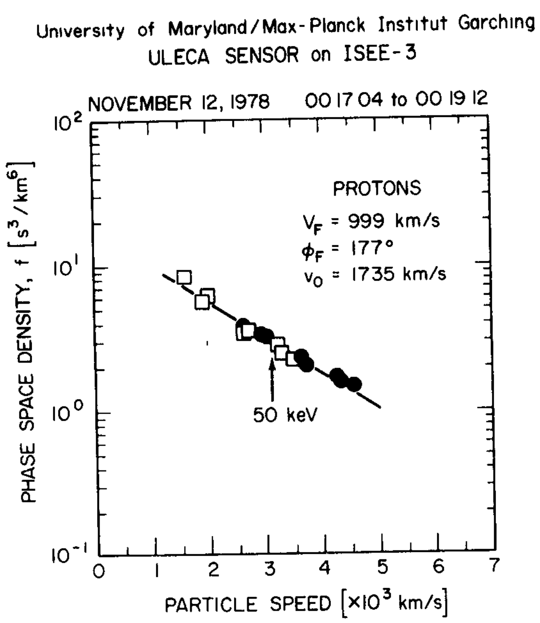


Figure 1. Rest frame proton phase space density, f(v). For $V_F$ = 999 km/s and $\phi_F$ = 177° segments of f(v) from the 33 keV proton rate channel (open squares) and the 66 keV channel (solid circles) join smoothly to form a common spectrum.

frame of reference (rest frame) in which f is assumed to be isotropic, and find the velocity, $\vec{V}_F$, of that rest frame relative to the spacecraft. We follow the technique of Gloeckler et al. (2) for mapping the sectored counting rate data into segments of the rest frame distribution function f(v), where v is the particle speed in the rest frame, making use of the invariance properties of f. When the proper rest frame velocity, $\vec{V}_F$, is chosen, the two segments of f(v) join up and the resulting spectrum becomes smooth, as shown in Figure 1. We note in particular that our method requires no prior knowledge of the shape of the rest frame energy spectrum nor need $V_F/v$ be small.

3. Observations. Using a least-squares technique we derive for each available 128 sec interval the rest frame velocity and the rest frame distribution function (over a range of particle speeds from ~1000 to 5000 km/s). Figure 1 shows an example of a 128 sec averaged distribution function f(v) obtained ~ $4 \cdot 10^{10}$ cm upstream of the shock. We note that the shape of f(v) tends to be between that of a pure power law and an exponential, and that the spectrum becomes harder with distance from the shock (3). In the present analysis an exponential form is assumed and the e-folding speed, $v_o$, is computed from a linear fit to the data as shown in the figure.

In Figure 2 we plot the derived speed, $V_F$, (solid circles) and direction of motion, $\phi_F$, (upper panel) of the suprathermal proton rest frame for each available 128 sec interval as a function of time as the shock is approached. Notice that the direction of $\vec{V}_F$ is generally within ~10° antisunward. Also shown is the sum of the solar wind, $V_{SW}$, and Alfvén, $V_A$, speeds taken (or derived) from data published in (5). While far ahead of the shock $V_F$ exceeds ($V_{SW} + V_A$) by as much as 1000 km/s, close to shock this difference is about a few hundred km/s, and behind the shock the two velocities are the same within experimental errors, implying pure convention at a speed equal to the sum of solar wind and Alfvén speeds. If we interpret the difference between the speeds $V_F$ and ($V_{SW} + V_A$) upstream of the shock to be the diffusive streaming of suprathermal ions along the magnetic field B (nearly radial for this shock) which results from the observed upstream particle density gradient, the local diffusion coefficient along B, $\kappa_\parallel (r_i,v)$ at a distance $r_i = (t_{sh}-t_i)V_{sh}$ from the shock ($V_{sh}$ and $t_{sh}$ are the shock speed and arrival times respectively) may be related to quantities measured at $r_i$ as follows:

$$(1)\quad \vec{S} = 0 = [\frac{1}{3}\,v\,(\frac{\partial f}{\partial v})]*\vec{e}_B\cdot[\vec{V}_F(v)-(\vec{V}_{SW}+\vec{V}_A)] + \kappa_{\parallel}(r_i,v)*\vec{e}_B\cdot\vec{\nabla}f(v).$$

$\vec{S}$ is the differential streaming (which in zero is the particle rest frame), and $\vec{e}_B$ is the unit vector along $\vec{B}$. Since for the November 12, 1978 shock $\vec{B}$ and $\vec{V}_{SW}$ were nearly radial, and assuming that $\vec{V}_A$ was directed along $\vec{B}$ in the upstream region, and that f(v) has an exponential dependence on v with e-folding speed $v_o$, eq. (1) may be simplified to

$$(2)\quad \kappa_{\parallel}(r_i,v) = [\frac{v}{3v_o}]*[\frac{256\cdot 10^{10}}{\ln(f_{i+1}/f_{i-1})}\,V_{sh}]*[V_F-(V_A+V_{SW})].$$

To obtain $\kappa$ at a distance $r_i$ upstream of the shock values for $v_o$ are obtained from the slope of the ith distribution function, and the particle density gradient is determined from the neighboring values of f at v = 3100 km/s (50 keV). $V_F$ and $(V_A + V_{SW})$ are those plotted in Figure 1 at times $t_i$ related to $r_i$ by $r_i=(t_{sh}-t_i)V_{sh}$, where we used values for $V_{sh}$ of 612 km/s and $t_{sh}$ of 0:28:18 as given in (5).

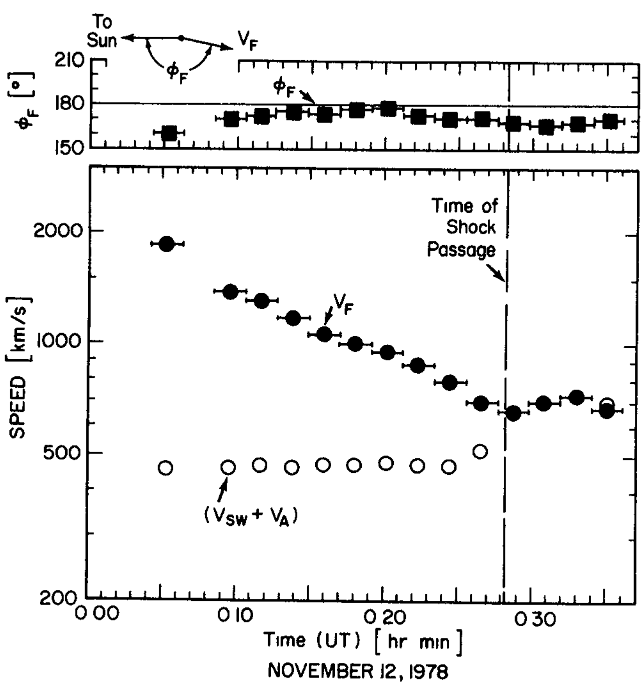


Figure 2. Speed and direction of motion of the rest frame (solid symbols) and the solar wind plus Alfvén speed $(V_{SW} + V_A)$ vs time before and immediately after shock passage. The difference between $V_F$ and $(V_{SW} + V_A)$ is interpreted in terms of diffusive streaming. Behind the shock $V_F \simeq (V_{SW} + V_A)$ implying pure convection of 50 keV protons at that speed.

## 4. Spatial Dependence of $\kappa_{\parallel}$.

In Figure 3 we show values of $\kappa_{\parallel}$ for ~ 50 keV protons as a function of distance from the shock, where $\kappa_{\parallel}$ is computed using eq. (2). The uncertainties shown come primarily from inaccuracies in determining the local density gradients. We note that there may be systematic errors ($\lesssim$30%) in the values of $\kappa$ resulting from using the simpler eq. (2) rather than eq. (1) which incorporates vector quantities. Consistent with expectations (7) we find that $\kappa$ increases exponentially from a value of $\sim 7\cdot 10^{17}$ cm$^2$/s near the shock to $\sim 2.5\cdot 10^{18}$ cm$^2$/s at ~ $4.5\cdot 10^{10}$ cm from the shock with an e-folding distance of $3.4\cdot 10^{10}$ cm. What is surprising is the subsequent decrease (again exponential, with e-folding distance of $\sim 1.1\cdot 10^{10}$ cm) in the value of $\kappa$ with distance from the shock.

5. Discussion and Conclusions. The factor of $\sim$ 4 increase in $\kappa$ over a distance of $\sim 4.5 \cdot 10^{10}$ cm is consistent with a comparable decrease in the power spectral density of waves at $2 \cdot 10^{-2}$ Hz (see Fig. 8 of ref. 7).

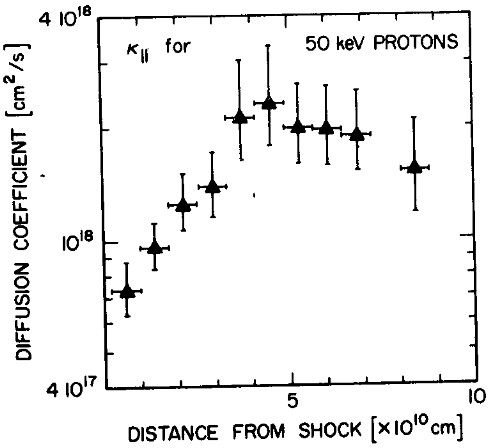


Figure 3. Spatial dependence of $\kappa_\parallel$ on upstream distance from the shock.

The value of $7 \cdot 10^{10}$ cm$^2$/s of $\kappa_\parallel$ (50 keV) near the shock is in excellent agreement with prediction (for this shock) based on a self-consistent theory for wave excitation and particle acceleration upstream of interplanetary shocks (7). Our values of $\kappa$ and its spatial dependence are also in qualitative agreement with those reported in (6,9). What is puzzling is the decrease of $\kappa_\parallel$ (50 keV) at larger distances which is not predicted by current theory. To pursue this point further we computed $\kappa_\parallel$ (100 keV) following the procedure outlined above but now using the 66 and 132 keV proton counting rate data. We found that the rest frame speeds $V_F$ characteristic of ~100 keV protons are smaller than those shown in Figure 1 for 50 keV protons. Ratios of $\kappa_{100}/\kappa_{50}$ were determined to be ~3.0, 1.2 and 1.8 near the shock, at $r = 4 \cdot 10^{10}$ cm and $8 \cdot 10^{10}$ cm respectively. Assuming a simple power law dependence of $\kappa$ on particle energy these values correspond to $\kappa \propto E^{+1.6}$, $E^{+0.26}$, $E^{+0.85}$ respectively. We therefore conclude in agreement with (9) that one cannot characterize the energy dependence (or the spatial dependence) of $\kappa$ in a simple way. Our results indicate an increase in the wave power density beyond $r \sim 5 \cdot 10^{10}$ cm and in general a more effective scattering of 50 keV protons compared to 100 keV protons. This hypothesis can be checked using local wave power spectrum measurements as a function of distance from the November 12, 1978 interplanetary traveling shock.

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