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THE TIME SCALES OF THE SCATTERING OF ENERGETIC PROTONS IN INTERPLANETARY SPACE

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ABSTRACT

Observations with the directional spectrometer DFH aboard ISEE3 have been used to obtain results on the scattering time scales of energetic protons. Depending on the duration of the scattering process the particle distribution will be subjected to either phase scattering or full scattering. Our analysis of some representative events shows that full scattering is applicable to shock-associated events.

INTRODUCTION

The analysis of processes acting on energetic particles in interplanetary space, in particular the scattering process, is most straightforward in the rest frame of the solar wind plasma: the magnetic irregularities, which scatter the particles are stationary in this frame (if we neglect their phase velocity) and the electrical field $\vec{E}' = 0$. The scattering causes a relaxation of the particle distribution towards an equilibrium with the solar wind frame. Depending on the duration τ of the scattering process we can distinguish three stages in this relaxation /1/ ($\tau_s=\lambda/v$ is the scattering time scale, where λ is the mean free path and v the particle velocity):

1. $\tau \ll \tau_s$.
   The source distribution is not substantially influenced by scattering. This is the case when the distance travelled by the particles between source and observer is significantly less than one mean free path.
2. $\tau \approx \tau_s$, phase scattering.
   The scattering process has erased the phase dependence in the initial particle distribution. The distribution is in equilibrium with the $\vec{E} \times \vec{B}$ drifting frame.
3. $\tau \gg \tau_s$, full scattering in both phase and pitch-angle.
   The scattering process has erased all angular dependence in the initial particle distribution. The distribution is in equilibrium with the solar wind frame.

(This does not mean that the distribution has become isotropic in the equilibrium phrame. In shock-associated events, for example, scattering and acceleration of particles is a continuous process, which maintains a certain anisotropy.)

At the location of ISEE3 (approximately 0.01 AU from the earth) the first condition is met by upstream particle events (UPE). In shock-associated events, where particles and shock originate at the sun (flare-associated), one of the last two conditions must hold. The ISEE3 data enable us to discriminate between these two possibilities and we will show that in shock-associated events observed at the ISEE3 location full scattering is applicable.

EQUATIONS AND ANALYSIS PROCEDURE

We assume that the scattering at the shock contributes only a pitchangle dependence to the distribution function i.e. in the equilibrium frame the (shock-induced) anisotropy $\vec{I}_s$ is parallel to the magnetic field:

$$\vec{I}_s = I_s\,\hat{B} \tag{1}$$

The equilibrium frame, however, moves with velocity $\vec{U}$ with respect to the satellite frame in which the observations are obtained ($\vec{E}=-\vec{V}\times\vec{B}$, $\vec{V}$ is the solar wind velocity):

$$\vec{U}=\begin{cases}\vec{V} & \text{(full scattering)}\\ \vec{V}_\perp = \vec{E}\times\vec{B}/B^2=\vec{V}-(\vec{V}.\hat{B})\hat{B} & \text{(phase scattering)}\end{cases} \qquad (2)$$

Transformation of the particle distribution function from equilibrium frame to satellite frame involves the Compton-Getting correction, which to first order comes down to adding an extra anisotropy /2/

$$\vec{I}_{CG}=I_0\,\frac{\vec{U}}{V}\,,\ \text{where}\qquad I_0 = -\,\frac{V}{v}\cdot\frac{d\,\log\,f(v)}{d\,\log\,v} \qquad (3)$$

The observed anisotropy is

$$\vec{I}=\vec{I}_s+\vec{I}_{CG} \qquad (4)$$

If we define the x-axis by $\hat{x}=-\vec{V}/V$ (the sunward direction) we obtain (combining 1 through 4)

$$\begin{aligned}\vec{I}.\hat{B}/I_0 &= I_s/I_0 && \text{(phase scattering)}\\ \vec{I}.\hat{B}/I_0 &= I_s/I_0 - B_x/B && \text{(full scattering)}\end{aligned} \qquad (5)$$

The procedure was to look for a linear correlation between $\vec{I}.\hat{B}/I_0$ and B_x/B. Plots of these quantities should show a straight line with slope 0 for phase scattering and -1 for full scattering. However, this correlation test has two limitations. First, the vector-picture used is a first order approximation, so the test is meaningfull only when the anisotropy is small, $I<1$ (the maximum possible anisotropy is $\sqrt{3}$). In practice this means that often observations immediately prior to shock passage cannot be used. Second, if the quantity I_s changes on a time scale shorter than the minimum time interval necessary for the test to be statistically significant (≈0.5 hours) no meaningfull correlation will be found and it is not possible to draw any conclusions on the nature of the scattering.

RESULTS

The data used were recorded by the energetic protons instrument ISEE3/DFH, sensitive in the energy range 35-1000 keV /3/. Twelve shock events in the years 1978-80 were investigated; three representative examples are shown in figures 1 through 3. Fig. 1b shows the results for a period of approximately 8 hours taken from the shock event on 6 June 1979 (fig. 1a). The linear correlation coefficient is large (r=.97) and the slope of the line (s=-.98±.01) implies full scattering. Fig. 2, taken from the event on 28 March 1979, shows a period of 13 hours with a discontinuity feature that occasionally arises in intensive events. The correlation for the total period is hardly significant (r=.81), however, if the test is separately applied to the periods before and after 22:45:40 hours there is a definite improvement: r=.89, s=-.95±.06 resp. r=.93, s=-.93±.02. Apparently we are dealing with a case of full scattering with a sudden change in the anisotropy I_s at time 22:45:40. Fig. 3 shows a period of 2 hours close to shock passage of the event on 1 April 1979. The correlation coefficient r=.72 is in itself too low to draw any conclusions. If, however, we bring out the chronological order of the data by connecting them as is done in fig. 3b, a picture of several separate structures arises, which are all lying along lines with a slope of approximately -1, which is a typical feature during more variable parts of the shock events. Even in this case, where the anisotropy I_s varies on a time scale (≈1 hour) only marginally larger than the minimum time interval required for statistical significance it appears to be possible to decide in favour of full scattering. Summarizing the results we can say that, in all cases with significant correlation, the resulting straight line has a slope of ≈ -1, i.e. full scattering dominates these shock events. Fig. 4 shows some UPE's on 14 April 1979, which represent a physically different situation, as the distance source-observer (earth-ISEE3) is significantly smaller than the mean free path. The expected absence of a correlation is confirmed (r=.03).

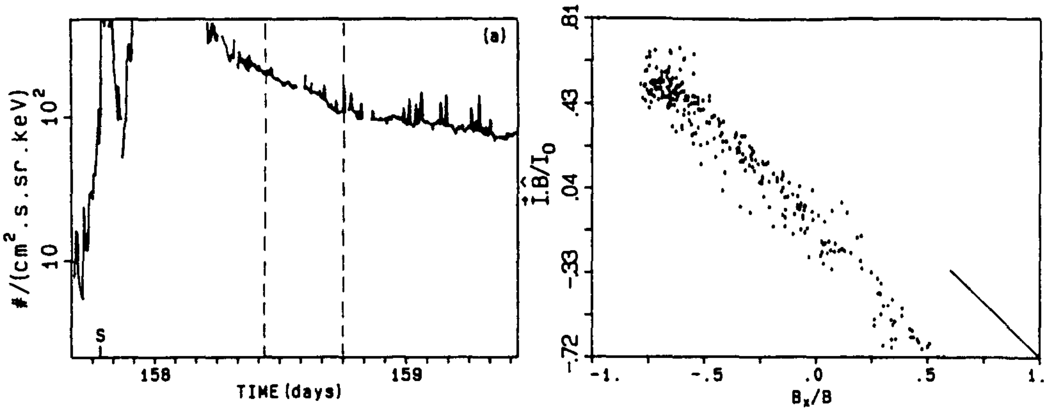

Fig. 1. a) Omni-directional intensity (57-91 keV) of the shock event on 6 June 1979 (day 157). "s" denotes time of shock passage. b) Correlation test for the interval 158/10:32-18:00. Each point represents a 80 sec time average. The slope of the line starting from the lower right corner corresponds with the "full scattering" slope -1.

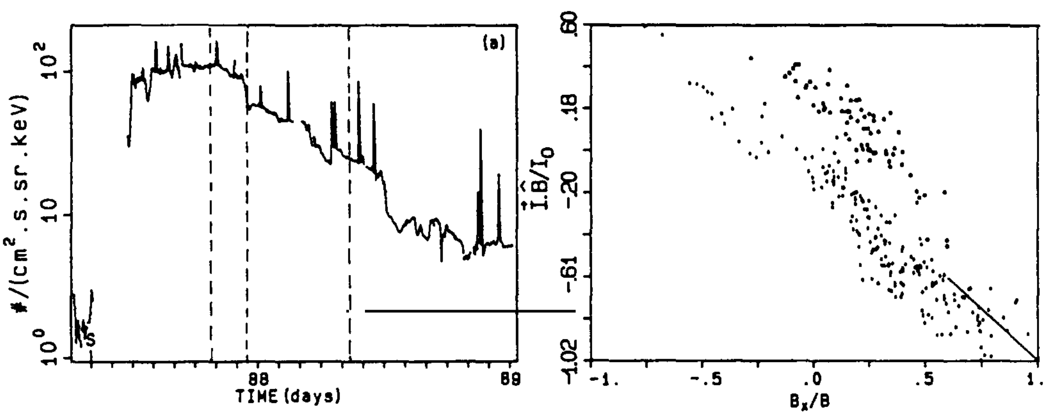

Fig. 2. a) Omni-directional intensity (57-91 keV) of the 28 march 1979 (day 87) event with time of shock passage (s). b) Correlation test for the interval 87/19:30-88/8:40. Each point represents a 160 sec time average. The "full scattering" slope -1 is shown in lower right corner. Data earlier than 22:45:40 appear as bold dots, data later than 22:45:40 as small dots.

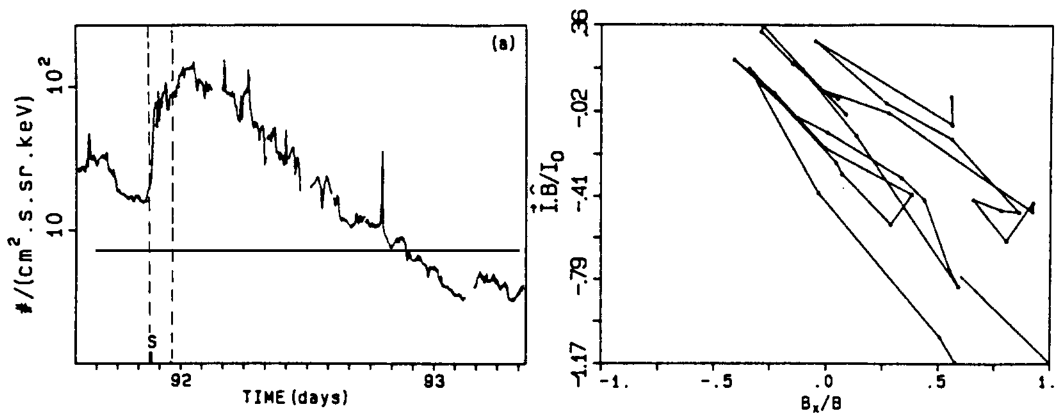

Fig. 3. a) Omni-directional intensity (57-91 keV) of the 1 April 1979 (day 91) event with time of shock passage (s). b) Correlation test for interval 91/21:08-22:53. Each point represents a 160 sec time average. The "full scattering" slope -1 is shown in lower right corner; The line connecting the points indicates the chronological order of the data.

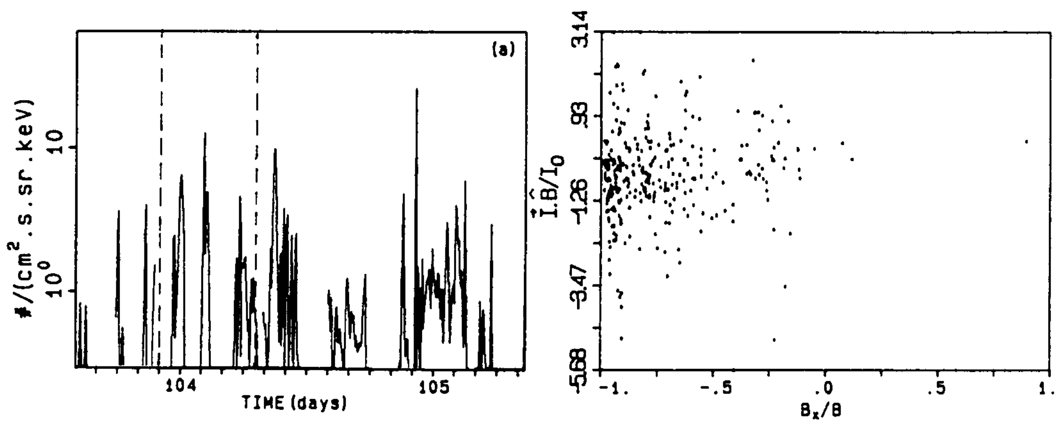

Fig. 4. a) Omni-directional intensity (57-91 keV) of UPE's on 14 April 1979 (day 104). b) Correlation test for interval 103/22:01-104/7:01. Each point represents a 80 sec time average.

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