Dynamics of Solar Energetic Particles in the Presence of a Shock Wave

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Abstract

From the analysis of problem solutions on the solar energetic particle propagation in the presence of a plane shock wave described by the diffusion convective transport equation, the condition and manifestations for the influence of a shock wave on the SEP propagation in the solar wind have been determined.

Solar energetic particles (SEP) in gradual events are generated by shock waves (see, for example, [1] and references there). The SEP generation region is limited, on the whole, by the solar corona. Proton fluxes of 470 MeV to 21 GeV energies, a maximum of which occur at a time when the shock in the atmosphere of the Sun reaches heights equal to 5 – 10 solar radii [2] indicate to it. It is also confirmed by the significant advancing of the occurrence time of maximum in the SEP intensity with kinetic energies more than 10 MeV relative to the shock front arrival moment to Earth's orbit. Model calculations for the particles acceleration by the diffusive mechanism in conditions, typical for the solar corona, show that the time taken to pass the solar atmosphere by the shock is quite sufficient to form the particle spectrum corresponding to the SEP characteristics observed [3,4].

Lee and Ryan [5] investigated the problem of SEP gradual event generation, propagation and confirmed the close association between the diffusive acceleration mechanism and SEP events. The absence of depending of particle diffusion coefficients on the energy is a lack of this model.

As an extension of preceding investigations, in this work the temporal dynamics of the particle spectrum in the presence of a plane shock for diffusion coefficients depending on the particle energy and also their change in time is studied.

The SEP event from a moment of arising of a shock to a moment of it's arrival on the Earth's orbit can be divided on two stages: the first stage (duration is ~ 1 hour) is a generation of SEP in the solar corona, the second stage (duration is ~ 1 day) is a propagation in interplanetary space in the presence of a shock. Here we consider the second stage only which as believed to be began with the injection of the particle spectrum formed during the first stage.

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The solution of the transport equation in the diffusive approximation

$$\frac{\partial f_i}{\partial t} = k_i \frac{\partial^2 f_i}{\partial x^2} - u_i \frac{\partial f_i}{\partial x}$$

with zero initial and boundary conditions at $x \rightarrow \pm\infty$ and sewing conditions of solutions at the shock front defines the particle distribution in the presence of a shock (see [6], in detail).

The general solution in space with a plane geometry and diffusion coefficient of particles depending on the momentum only can be presented in the form of two analytic relations: 1) the distribution function of particles at the shock front depending on injected particle flux and 2) the distribution function of particles in space depending on the distribution function of particles at a front.

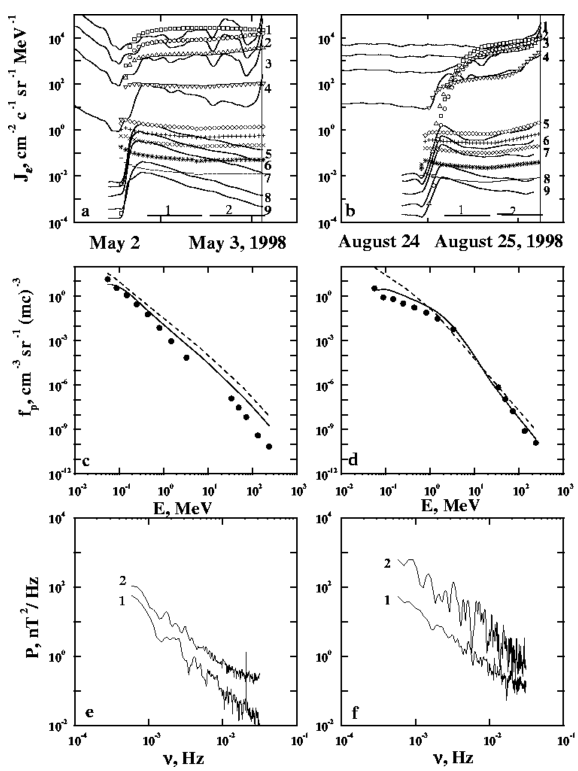

Fig. 1. The panel a is intensity of SEP in the May 2, 1998 event depending on the time. The panel c presents the distribution function of particles at the shock front depending on the energy. The panel e gives the IMF power spectrum density. The panels b, d, f are the same for the August 24, 1998 SEP event.

Fig. 1. shows results of calculation and measurements of SEP events on May 2 and August 24, 1998. Curves 1 – 9 in the panels a, b are SEP intensity depending on the time registered in the Earth's orbit in 9 energetic channels: 1 –

0.047-0.065; 2 – 0.112-0.187; 3 – 0.31-0.58; 4 – 1.95-4.75; 5 – 27-41; 6 – 41-58; 7 – 58-88; 8 – 88-180; 9 – 180-300 MeV.

Curves from marks are the calculation for the energy corresponding to a center of energetic channel. A vertical solid line in the panels a, b is a moment of the shock arrival. Curves in the panels c, d are the distribution functions of SEP at the shock front: the dashed and solid curves are the calculation for the injection moment and shock front arrival moment to the Earth's orbit, respectively; points are measurements in the Earth's orbit. Curves marked by 1, 2 in the panels e, f are the power spectrum density of the interplanetary magnetic field (IMF) determined for two time intervals marked by horizontal lines in the panels a, b.

Results of measurements are obtained from two spacecraft - ACE: a) hourly data of SEP flux measurements (curves 1 – 4 in the panels a, b) are EPAM/LEMS30 experiment; b) hourly data of solar wind parameter measurements are SWEPAM experiment; c) hourly and 16-s data of IMF measurements are MAG experiment; and INTERBALL – 2: hourly data of proton flux obtained with 10K-80 spectrometer (curves 5 – 9 in the panels a, b).

According to measurements, in calculations the following values of parameters are used: for May 2 event: $w = 500$ km/sec is the solar wind velocity in the region before the shock; $V_S = 1070$ km/sec is the shock speed according to the disturbance propagation time; $\sigma = 4$ is a degree of compression matter in the shock front; $B = 6$ nT is IMF intensity before the shock; for the August 24 event: $w = 400$ km/sec; $V_S = 1300$ km/sec; $\sigma = 3$; $B = 6$ nT.

The diffusion coefficient used in these calculations is determined according to a quasilinear theory [7]. Taking into account numerical values the expression for it in the region before the shock front can be described in the form: $k_1 = \frac{3.6\cdot 10^{11}}{P(\nu_0)} \left(\frac{B}{5nT}\right) \left(\frac{\varepsilon}{1MeV}\right)^{\frac{3-\alpha}{2}}$ (cm^2/sec), where $P(\nu) = P(\nu_0)(\nu/\nu_0)^{-\alpha}$ is the IMF power spectrum density; $\nu_0 = 2.2 \cdot 10^{-3}(B/5nT)(w/400\ km/sec)$ (Hz) is the frequency of Alfven waves interacting resonance with protons whose energy equals 1 MeV. In the May 2 event, as it is followed from the panel e, $\nu_0 = 3.3 \cdot 10^{-3}$ (Hz); $\alpha = 1.9$; $P(\nu_0) = 1(nT^2/Hz)$ that gives $k_1 = 4.3 \cdot 10^{21}(\varepsilon/1MeV)^{0.55}$ (cm^2/sec).

According to measurements of the IMF power spectrum (curve 2 in the panel e), the diffusion coefficient in the second part of this event decreased by 3 times. In accordance with data for the August 24 event (the panel f): $\nu_0 = 2.6 \cdot 10^{-3}$ (Hz); $\alpha = 1.5$; $P(\nu_0) = 6(nT^2/Hz)$ that gives $k_1 = 0.72 \cdot 10^{21}(\varepsilon/1MeV)^{0.75}$ (cm^2/sec), which decreases in the second part of event by 10 times. As concerns the diffusion coefficient of particles in the region beyond the shock front, it is taken in both events that $k_2 = k_1/10$ always.

As evident from results presented in the panels a, c, e the SEP event on May 2 taken place on the background of a low level of turbulence, among them at its increase by a factor of 3 in the second part of event. As a result, the manifestations of the regular acceleration mechanism in the temporal dynamics of SEP intensity are absent. Local variations in the low-energy SEP intensity (curves 1 – 3 in the panel a) are apparently due to large-scale magnetic clouds from preceding disturbances which at that time moment intersected the Earth's orbit. On the whole, the results of calculations for this event are qualitatively consistent with experiment.

The SEP dynamics in the August 24 event because of the higher turbulence level (curves 1, 2 in the panel f) is defined by the diffusive acceleration process: the shock front acts strongly on low-energy particles (curves 1 – 4 in the panel b) and weakly on high-energy particles (curves 5 – 7 in the panel b). The results of calculations and measurements are consistent with each other.

The the significant decrease of the diffusion coefficient of particles in the region before the shock during the event intensities the diffusive acceleration process. Results of IMF power spectrum measurements on-line can be used for a forecast of the high-energy SEP intensity increases up to the arrival moment of the shock front. It is of important interest for Space Weather problems.

The dynamics of the particle intensity calculated in the framework of diffusion approximation with diffusion coefficients estimated according to the quasilinear theory for the measured IMF power spectrum qualitatively corresponds to the SEP intensity observed. Measurement data of the IMF power spectrum density during an event on-line can be used for the forecast of high-energy SEP intensity increases up to the shock front arrival moment.

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