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Solar energetic particles: Characteristics of transport in interplanetary space by measurement on INTERBALL–2

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Abstract. The events of the intensity increase of energetic solar particles are analyzed on the basis of data of the 10K-80 spectrometer installed aboard the ”Interball-2”. The analysis of four solar cosmic ray events based on the comparison of measured solar cosmic ray fluxes and calculated ones allows to make the definite conclusions:

1. The particle propagation model in interplanetary space, which takes into account the impulsive injection in time and their diffusive propagation only along the interplanetary magnetic field lines, describes, on the whole, real events.

2. Considerable generation of turbulence by the solar energetic particles flux and high speed of shock can result in the increasing of magnitude of flow up to arrival of a distubance.

3. At the beginning of the 23 rd solar cycle maximum the total number of the injected particles and their total energy in individual events were $N > 10^{35}$ particles, $E > 10^{29}$ erg, respectively.

1 Introduction

According to modern representations, solar energetic particles (SEP) are subdivided into two classes having a different generation: impulsive and gradual events. Suppose, that SEP of impulsive events are generated in the lower corona of the Sun by means of the statistical acceleration mechanism, and SEP of gradual ones — in the upper corona by shocks (Reames , 1999, 2000). After generation in the solar corona SEP of both classes are injected in interplanetary space, where they are propagated by kinetic (in case of weak scattering) or diffusive (in case of strong scaterring) ways. By comparison of the calculated and measured flows of 4 event SEP the characteristics SEP and the diffusion coefficients in interplanetary medium are determined, two versions of propagation SEP at the presence of a solar wind large–scale disturbances are discussed.

2 The Model

At propagation SEP in interplanetary space the condition $wr_e << K(\varepsilon)$ is usually satisfied, meaning that the spatial diffusion of particles is a main process. Here w is the solar wind speed; $K(\varepsilon)$ is a diffusion coefficient; $r_e = 1AU$. For conditions which are usually fulfiled in interplanetary medium – 1) the particles are magnetized ($K_\perp(\varepsilon) << K_{||}(\varepsilon)$), 2) the cross section of a power tube of an interplanetary magnetic field (IMF) increases as a square of distance – an equation of propagation for a differential spectrum $n(\varepsilon, r, t)$ looks like

$$\frac{\partial n}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 K_{||}(\varepsilon, r)\frac{\partial n}{\partial r}\right) ,$$

where $K_{||}(\varepsilon)$ is ($K_\perp(\varepsilon)$) a diffusion coefficient of particles along (across) of IMF lines. In a case $K_{||} = K_{||,e}(\varepsilon)(r/r_e)^\beta = K_0(\varepsilon/1MeV)^\nu(r/r_e)^\beta$ the equation has the solution (Krimigis , 1965):

$$n(\varepsilon, r, t) = \frac{N_i(\varepsilon)}{\Omega} \cdot \left((2-\beta)^{\frac{4+\beta}{2-\beta}} \cdot \Gamma\left(\frac{3}{2-\beta}\right)\right)^{-1} \times$$

$$\times \left(\frac{r_e^\beta}{K_e(\varepsilon)t}\right)^{\frac{3}{2-\beta}} \cdot \exp\left(-\frac{r_e^\beta}{K_e(\varepsilon)t} \cdot \frac{r^{2-\beta}}{(2-\beta)^2}\right) , \qquad (1)$$

where $N_i(\varepsilon)$ is a differential spectrum of injected SEP; Ω is a solid angle of the volume occupied by injected particles; $\Gamma\left(\frac{3}{2-\beta}\right)$ is a gamma–function; the index e means values of parameters referred to the Earth orbit. The correspoding differential SEP flow is determined by the expression

$$J(\varepsilon, r, t) = \frac{n(\varepsilon, r, t)\upsilon}{4\pi} = \sqrt{\frac{\varepsilon}{8\pi^2 m}} \cdot n(\varepsilon, r, t),$$

where υ, m, ε are the velocity, mass and kinetic energy of a proton.

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Table 1. The observational data for SEP events.

Date	Coordinates	$t_{0_{H_\alpha}}$, UT	t_{max} UT
November 4, 1997	S14W33	0558	1120
May 2, 1998	S15W15	1342	1650
May 6, 1998	S15W65	0809	0945
August 24, 1998	N30E07	2212	August 25 , ∼0100

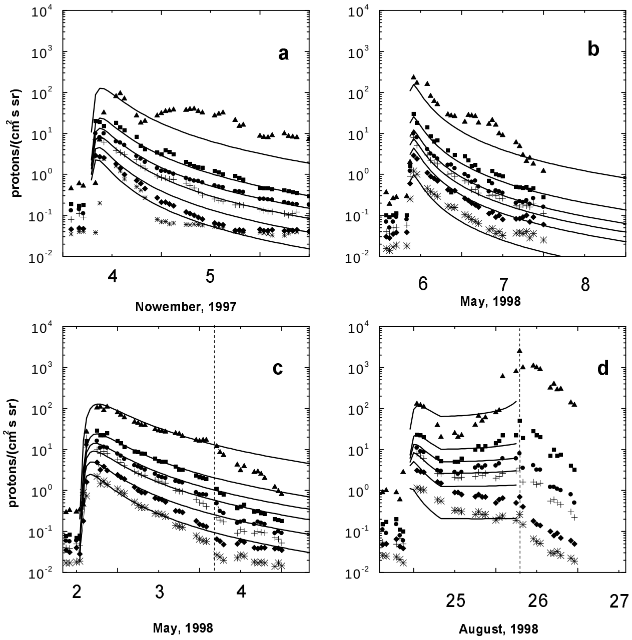

Fig. 1. Symbols are the proton fluxes measured onboard the "Interball-2" versus the time of solar flares on November 4, 1997, May 2, 1998, May 6, 1998 and August 24, 1998 and solid lines are calculated ones.

A concominant large–scale disturbance — the coronal mass ejection (CME) followed by a shock — can exert influence on propagation of SEP in gradual events in interplanetary medium. In volume ahead of disturbance the condition is usually satisfied, $R_S V_S << K(\varepsilon)$ which are confirmed considerably faster propagation in space of SEP than CME (Berezhko et al. , 2001). Here R_S, V_S are the radius and speed of a shock. The condition, as well as above mentioned, means that the main process of SEP propagation ahead of shock is their spatial diffusion. CME can influence this propagation, as the particles weakly pass into perturbed volume owing to a high level of turbulence in it. One can receive the estimation of influence from simple reasons: the amplitude of a SEP spectrum for decay phase, i.e. after a maximum of flow, is determined by a ratio

$$n(\varepsilon, t) \sim \frac{1}{V_1(t) - V_2(t)}, \tag{2}$$

where $V_1(t)$ is a volume of a IMF tube, occupied by SEP; $V_2(t)$ is a similar volume occupied by a disturbance. In case of diffusive propagation of particles $V_1(t) \sim l^3 \approx (6K_{||}(\varepsilon, t)t)^{3/2}$, whereas $V_2(t) \sim R_S^3(t)$. Here l is a length of a power tube of IMF. At $V_1(t) >> V_2(t)$ the diffusive propagation of SEP, described by the solution (1) prevails; in case $V_1(t) \sim V_2(t)$ up to arrival of a disturbance the increasing of a flow SEP magnitude can be observed.

Owing to east - western asymmetry of IMF, conditioned by its spiral structure the given effect can be manifested stronger for central and western disturbances. The angular borders of effect are determined by the angular sizes of CME.

3 Calculation Results and Discussion

In Fig. 1 the flows of protons versus the time, measured in experiment in the framework of "Interball–2" for solar flares of November 4, 1997, May 2, 1998, May 6, 1998 and August 24, 1998 which has occurred during a phase of 23–rd cycle of solar activity rise, and calculated ones are shown. The device 10K-80 aboard "Interball–2" registered a flow of protons in 6 energetic channels at $\varepsilon > 7$ MeV and 5 "differential" channels at 27–41, 41–58, 58–88, 88–180, 180–300 MeV (Timofeev and Starodubtsev , 1999, 2000). The gaps of the data are connected with interception by the vehicle of the Earth radiation belts. The calculation results are shown by the solid lines. Symbols are the measurements in different energetic channels.

The differential spectrum of protons, injected into interplanetary space, is approximated by a power law function $N_i(\varepsilon) \sim \varepsilon^{-q_k}$, where $\varepsilon_k \leq \varepsilon \leq \varepsilon_{k+1}, k = 1, 2, ...6$; $\varepsilon_1 =$ 7MeV; $\varepsilon_2 = 27$ MeV; $\varepsilon_3 = 41$ MeV; $\varepsilon_4 = 58$ MeV; $\varepsilon_5 = 88$ MeV; $\varepsilon_6 = 180$ MeV; $\varepsilon_7 = 300$ MeV; $N_i(\varepsilon_1) = N_0$; q_k are the set of indices of a spectrum and N_0 in calculations defines the amplitude of flow in first energetic channel. We consider, that the injection of SEP moment coincides with

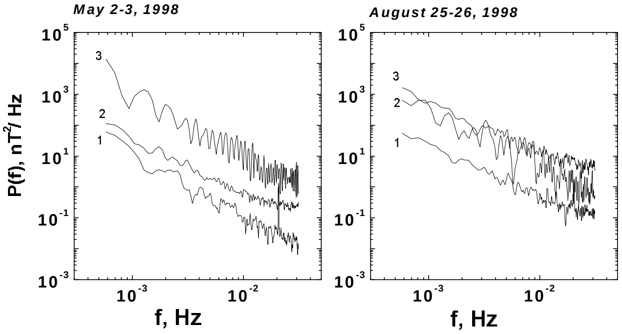

Fig. 2. The power spectral density IMF module for May 1998 and August 1998 events. left: 1 — May 2–3, 1998 1500–0300 UT, 2 — May 3, 1998 0300–1500 UT, 3 — May 3–4, 1998 1400–0200; right: 1 — August 25, 1998 0200–1400 UT, 2 — August 25–26, 1998 1800–0600 UT, 3 — August 26, 1998 0700–1900 UT.

Table 2. The calculation results of main SEP characteristics

Date	q	ν	β	$N_0 \cdot 10^{33}$, $particles \cdot MeV^{-1}$	$K_0 \cdot 10^{21}$, cm^2/s	$N/\Omega \cdot 10^{35}$, $particles/sr$	$E/\Omega \cdot 10^{29}$, erg/sr	Ω, sr
November 4, 1997	1.2–3.4	0.30	0.70	1.07	2.0	1.20	4.20	≥ 0.46
May 2, 1998	1.2–3.4	0.10 (0.70)	0.25 (0.80)	1.07	3.0 (9.1)	1.20	4.20	≥ 2.24
May 6, 1998	1.4–3	0.00 (1.15)	0.25 (2.60)	1.22	8.0 (110.0)	1.85	5.47	≥ 0.2
August 24, 1998	1.3–3.3	0.00 (0.80)	0.00 (1.20)	0.83	6.0 (1.2)	1.08	3.44	≥ 4.34

the moment of a maximum of brightness in H_α of the corresponding flare.

The main properties of SEP and solar flares are listed in the Tables 1, 2. Columns the Table 1 are : 1 — date of solar flares registered onboard "Interball–2 "; 2 — coordinates of the corresponding solar flares; 3 — time of a maximum of brightness in H_α; 4 — time of a maximum of a SEP flow with energy $\varepsilon > 10$ MeV, registered on the Earth orbit. Columns of the Table 2 are : 2 — an interval of values of a index of the injected particle spectrum, q; 3 — parameter which takes into account relation of a diffusion coefficient versus energy, ν; 4 — parameter taking into account spatial relation of a diffusion coefficient, β; 5 — amplitude of a differential spectrum SEP in a source, N_0; 6 — a diffusion coefficient SEP with energy 1 MeV at $r = r_e$, K_0; 7 — the density of number SEP with $\varepsilon \geq 7$ MeV in unit of solid angle, N/Ω; 8 — the density of a kinetic energy of SEP with energy $\varepsilon \geq 7$ MeV in unit of solid angle, E/Ω; 9 — value of solid angle of volume, in which SEP were injected Ω. The estimation of minimum value of solid angle is made in the supposition of an azimuthal symmetry of a SEP flow concerning an axis passing through a point on a surface the Sun coinciding with the solar flare coordinates. As it is visible from comparison events, presented on Fig. 1a, b in general can be described by the solution (1) with parameters listed in the Table 2. The nonmonotone behavior of flows SEP in an integral channel, apparently, mirror the effect of magnetosphere. The difference between the calculated and measured flows in last differential channel, representing in a Fig. 1a is explained that in the beginning of November 5 the SEP flow of these energies has reached a background level.

The parameters of a diffusion coefficient computed according to the quasilinear theory (Lee , 1982) for all events of 1998, are adduced in brackets in columns 3, 4 of Table 2. The corresponding parameters of turbulence were determined by 16-sec values of a module of IMF, measured device onboard ACE. Power spectral density of IMF is determined in a 12-hour time period after maximum of the corresponding SEP flow and was approximated by a function: $P(f) = P_0 f^{-\alpha}$, where f — frequency; P_0 — a constant of a spectrum at $f = 1$ Hz; α — a spectral index. The corresponding parameter of events in 1998 are listed in Table 3, where B_0 and U_0 are average values of a module IMF and speed of a solar wind for this time. A diffusion coefficient, computed according to the quasilinear theory and utilised in model on propagation of SEP, demonstrates differences. It may be connected that temporary dynamic of a SEP flow is determined by conditions in a large volume of the space, while the measurements of properties of IMF fall into to a local volume.

The events, presented in a Fig. 1c, d, occurred in presence of CME. In Fig. 2 the module of IMF spectra versus the time of these events for three time intervals are presented, from which two precede the arrival of CME. As it is seen from a Fig., the main difference is, that in event of May 2 the amplitude of spectrum for frequencies $f < 10^{-3}$ Hz down to the arrival of a shock marked by a vertical shaped line, has changed a little, while in the event of August 24 it has increased approximately by the order. This difference in behavior of a spectrum of IMF can explain different temporal dynamics of a SEP flow up to the arrival of CME. The capability of turbulence generation by a SEP flow has been proposed and studied in a number of theoretic papers and has confirmed by measurements (Berezhko , 1990; Wanner and Wilberenz , 1993; Starodubtsev , 1999; Tylka, Reames and Ng , 1999).

As follows from expression (2) the influence of a disturbance is possible under the condition of strong turbulence generation (the decrease of a diffusion coefficient) and high speed of a shock. In event of May 2 of the turbulence generation up to the arrival of a shock practically was absent, owing to the dynamic of a SEP flow down to the arrival of a shock, is described by the expression (1) at parameters of a diffusion coefficient indicated in the Table 2.

For the account of essential generation of turbulence in event of August 24 the combined description of dynamic of a SEP flow , presented on Fig. 1d is used: the flow up to an instant $t_* = 10$ hours after a particle injection is described by the expression (1) at a diffusion coefficient, whose parameters are presented in Table 2; at $t > t_*$ and up to the arrival of a shock the flow after the corresponding normalization is described by the expression (2) with a diffusion coefficient diminished by the order. For the radius and speed of a shock $R_S = V_{S0}((t/1hour)^{1-\kappa} - 1)/(1 - \kappa)$, $V_S = V_{S0}(t/1hour)^{-\kappa}$ are used, where $V_{S0} = 2000$ km/s,

Table 3. The parameters of events in 1998

Date	B_0, nT	$P_0 \cdot 10^{-4}$ $, nT^2/Hz$	α	$U_0 \times 10^7$, cm/s
May 2, 1998	11.35	1.0	1.62	5.3
May 6, 1998	7.63	5.5	0.69	4.6
August 24, 1998	6.78	6.8	1.43	3.9

$\kappa = 0.13$. Some disharmony of used kinematic parameters in comparison with the observed ones in the given event is explained by strong simplification of the model.

As a whole, for the given event it is possible to mark the qualitative agreement. The SEP event of August 24 is interpreted by other investigators as ESP event (Tylka, Reames and Ng , 1999). However at such explanation it is difficult to understand the observed softening of a spectrum of particles at the approach to a shock front.

4 Summary

1) The model of propagation of particles in interplanetary space which takes into account the impulse injection in time and diffusive propagation only along lines of IMF, in general, describes real SEP events . 2) Considerable generation of turbulence by a SEP flow and high speed of a shock can result in the increasing of magnitude of a flow up to the arrival of a disturbance. 3) In every of the reviewed events concerning the onset of a maximum of 23-rd cycle of solar activity there were a full number injected of SEP $N > 10^{35}$ and their energy $E > 10^{29}$ erg.

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