Solar Energetic Particle Spectra Produced by Shocks in Solar Corona

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Abstract

Energetic particle (ion) acceleration by shocks during their propagation through the solar corona is studied. Diffusive transport equation is solved numerically within the range of heliocentric distance where the efficient particle acceleration takes place. On later stages acceleration process becomes inefficient due to the decrease of Alfvénic Mach number and previously produced particles start to run away from the shock due to their progressively increasing mobility. These particles are observed in the interplanetary space as so called solar energetic particle (SEP) event. Calculated SEP spectra demonstrate good agreement with the experiment.

1. Introduction

There is now a general understanding that the largest and most energetic of the solar energetic particle (SEP) events are associated with shock waves driven out from the Sun by coronal mass ejections (CMEs) [1]. SEP in these so called gradual events have, on average, the same elemental abundances and ionization states as those in the solar corona plasma. Therefore it is suggested that SEP spectra are originated due to the diffusive shock acceleration during the shock propagation through the corona. First considerations [2,3] demonstrated that diffusive shock acceleration is able to generate SEP population consistent with observations. However, up to now it is not clear what are the most relevant physical factors which determine the SEP properties and why SEP population at some stage of the shock evolution become decoupled from the shock front and observed in the interplanetary space essentially ahead of the shock. We present here the model for the SEP production which is still not selfconsistent but which nevertheless includes: i) realistic set of corona parameters; ii) consistent description of temporal evolution of SEP spectra formed during the shock propagation through the corona; iii) shock geometry and adiabatic cooling which determine the upper SEP energy. Since the formation of the SEP spectra during the shock propagation through the corona was studied in our previous paper [4], here we present the expected SEP fluxes at the Earth's orbit and discuss their correspondence to the experiment.

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2. Results and discussion

We use the spherically symmetric model, based on the diffusive transport equation for CR distribution function $f(r,p,t)$ [4]. We neglect the shock modification by the pressure of accelerated particles, because it is essentially smaller than the ram pressure. Therefore the shock front is treated as discontinuity. The phenomenological source term in the transport equation describes the injection of some part $\eta = N_{inj}/N_1$ of medium particles N_1 into the acceleration process. The background Alfvén wave spectrum, which determines the particle diffusion, is taken in the form $E = E_0(k/k_0)^{-\beta}(r/R_\odot)^{-\delta}$, where E_0 is the wave energy density corresponding to the outer scale $L_0 = k_0^{-1}$ of turbulence at the lower corona edge $r = R_\odot$. We use the values $\beta = 0.5 \div 1.5$ and $\delta = 8$ which are consistent with the results of statistical studies of Faraday rotation fluctuations, performed for heliocentric distances between 3 and 34 $R_\odot$ [5]. The value of wave number $k_0 = 1.4 \times 10^{-6}$ cm^{-1} corresponds to the proton momentum $p = 0.5mc$, in the magnetic field at the Sun surface $B_* = 2.3$ G. The value $E_0 = 10^{-3}$ erg/cm^3, which is used in our calculations below, is consistent with the energy flux of Alfvén waves $F_w \sim 10^5$ erg cm^{-2} s^{-1} that is considered to be the main source of solar wind energy [6]. We consider here acceleration process in a linear approach not taking into account Alfvén wave generation due to accelerated particle streaming instability. Typical shocks driven by CMEs in the solar corona are not very strong: Alfvénic Mach number $M_a = u_1/c_a$ is usually less then 3. Therefore the spectrum of accelerated particles is relatively steep, the particle pressure is small compared with the ram pressure that provides not very intensive Alfvén wave generation. We employ the results of model [6] for the corona gas speed $w(r)$ and density $\rho(r)$ radial distributions.

Here we present the calculations of the SEP fluxes near the Earth's orbit and compare them with experiment. In order to calculate the expected intensity $J(r,\epsilon,t) = p^2 f(r,p,t)$ of SEPs with kinetic energy $\epsilon(p)$ at a given distance r we use the simple approach based on the transport equation for $f(r,p,t)$, where we neglect convection and adiabatic terms and take the source term in the form $Q = N_f(p)/(16\pi^2 p^2 R_f^2)\delta(t-t_f)\delta(r-R_f)$, where $R_f = R_s(t_f)$ is the shock size at the moment when acceleration process in the corona becomes inefficient, $N_f(p)$ is the overall differential spectrum of accelerated particles. Then assuming pure diffusive particle propagation in the outer region $r > R_f$, we define the SEP spectrum $I(\epsilon) = J_{max}(\epsilon)$ where $J_{max}(\epsilon) = J(r,\epsilon,t_{max})$ is the peak intensity of SEP achieved at distance r at time moment $t = t_{max}(r,\epsilon)$.

In Fig.1 calculated proton spectrum at $r = 1$ AU in the 1989 September 29 event together with the experimental data are presented. Calculation is performed for $V_s = 2000$ km/s, $E_0 = 6 \times 10^{-4}$ erg/cm^3, $\delta = 8$, $\eta = 4 \times 10^{-6}$. One can see that at low energies $\epsilon < 30$ MeV expected spectra are not sensitive to the Alfvén wave spectral index β and agree with the experiment. At larger energies

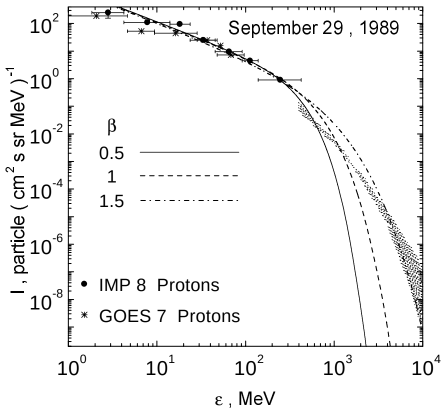

Fig. 1. Proton energy spectrum in the 1989 September 29 event including data points from IMP 8, GOES 7, the neutron monitor spectrum [8](shaded region) and calculated spectra for different Alfvén wave spectral index.

$\epsilon > 30$ MeV the exponential tail of the spectra becomes progressively flatter with the increase of β. The spectrum which corresponds to $\beta = 1.5$ satisfactory fits the neutron monitor data. The value of the cutoff energy ϵ_{max} growths rapidly with the increase of the shock speed V_s. We have performed the calculation of proton spectra for a large number of events. Consistency with the experimental data is almost always as good as shown in Fig.1.

High correlation between SEP events and CMEs has been found [9]. This relation is illustrated in Fig.2 where the measured peak intensities of protons with energy 2 MeV and 20 MeV are shown as function of the CME speed V_p together with calculations performed for the injection rate $\eta = 10^{-5}$ for three different Alfvén wave spectral indexes β. We use simple relation between the CME and the shock speed $V_s = [\sigma/(\sigma - 1)]V_p$, which corresponds to the piston driven shock. Here σ is the shock compression ratio. One can see that our theory very well reproduces strong dependence of the SEP peak intensities upon the CME speed for the most intense events. The spread of the observed peak intensities at a given CME speed can be due to the variation of the actual injection rate η.

It is very essential that the observed SEP fluxes are consistent with very low suprathermal particle injection rate $\eta \leq 10^{-5}$. Simple estimate shows that for such low injection not only shock modification by accelerated particle pressure backreaction but also the Alfvén wave excitation due to particle streaming instability can be neglected. It means that particle acceleration by the shocks in the solar corona can be adequately described within test particle approach, possibly except the case of extreme shock speed values $V_s \geq 1500$ km/s, when Alfvén wave excitation can play a role.

According to the measurements performed near the Earth's bow shock [10] the injection rate $\eta \sim 10^{-2}$ is much higher then required for SEP production. Since the efficiency of suprathermal particle injection goes down quickly when the shock becomes more and more oblique, this inconsistency can be explained if only small fraction of the shock during its propagation in the corona is quasi-parallel so that the actual injection rate averaged over the shock surface is much lower than its value for a pure parallel shock. It is also possible that not all energetic particles

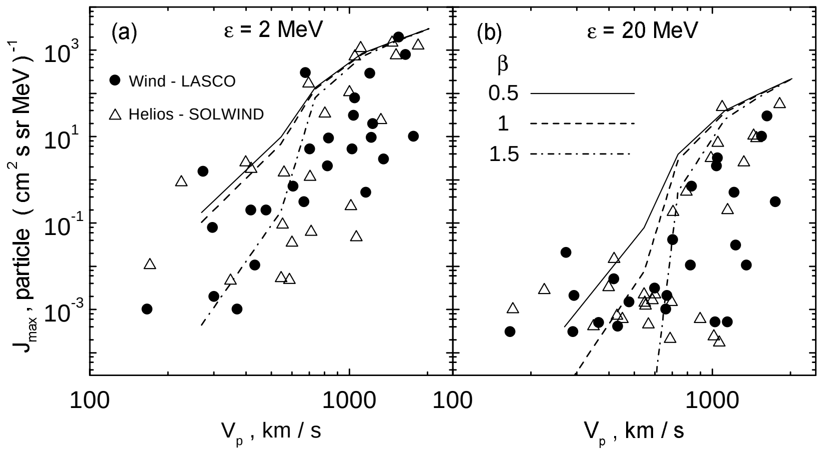

Fig. 2. Peak intensity of protons with energy 2 MeV (a) and 20 MeV (b) as a function of CME speed including the data points [9] and calculations for different Alfvén wave spectral indexes β.

accelerated in the corona are able to leave the shock interior as it is assumed. If an essential fraction of them are captured in the downstream region for a long period of time, then only some small fraction manifests themselves ahead of the shock as diffusively propagating SEPs.

Thus our consideration of ion acceleration by CMEs driven shocks demonstrates that under the reasonable assumption about the background Alfvén wave spectra consistent with their indirect measurements reproduces efficient particle acceleration in solar corona. Performed calculations demonstrates a good consistency consistent with observational properties of SEP events near the Earth's orbit.

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3. References

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