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Shock acceleration of energetic particles 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 up to 3 solar radius, where the efficient particle acceleration takes place. The values of corona parameters are taken from the observations. Due to high level of background Alfvénic turbulence and shock speed values the spectrum of accelerated particles is quickly formed during the initial period of shock propagation up to maximum energy of the order of 1 GeV. 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 presumably observed in the interplanetary space as so called solar energetic particle (SEP) event. Performed calculations demonstrate that the main characteristics of accelerated particles (their upper energy, spectral shape, energy content) are consistent with what is required to produce the observed SEP events.

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) (e.g. Reames 2000). These large so called gradual SEP-events essentially differ from more numerous events from impulsive flares (Reames, 1999), which are not considered here. SEP in gradual events have, on average, the same elemental abundances and ionization states as those in the solar corona plasma. Therefore it is natural to suggest that SEP spectra are originated due to the diffusive shock acceleration during the shock propagation through the corona.

First considerations (e.g. Ellison & Ramaty, 1985; Lee & Ryan, 1986) demonstrated that diffusive shock acceleration is able to generate SEP population with power law spectra up to the maximum energies $\epsilon_{max} \sim 0.1 \div 1$ GeV 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.

We does not consider here SEP elemental abundance and restrict our consideration by protons which is the dominant kind of ions in the corona.

2 Model

The front of the shock, driven out from the Sun by CMEs, has a complicated nonspherical form. We expect that the most effective acceleration takes place at the front part of it, where the shock velocity is the highest and the magnetic field has a small angle with the shock normal. This part of the shock is considered as a part of the sphere of radius R_s which increases in time with the speed $V_s = dR_s/dt$. We assume that the magnetic field $\boldsymbol{B}$ and the solar wind speed $\boldsymbol{w}$ are of the radial direction. Since the transverse size of the acceleration region $L_\perp$ is large enough ($L_\perp \sim R_s$), and fast particles are strongly magnetized, the spherical approximation can is applicable. In this case the diffusive transport equation for the particle (proton) distribution function $f(r,p,t)$ has a form

$$\frac{\partial f}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(\kappa r^2 \frac{\partial f}{\partial r}\right) - w'\frac{\partial f}{\partial r} + \frac{p}{3r^2}\frac{\partial (r^2 w')}{\partial r}\frac{\partial f}{\partial p} + Q,$$

where κ is the radial diffusion coefficient, p is the particle momentum, r is heliocentric distance, w' is the scattering

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centers speed. Due to the outward propagation of Alfvén waves $w' = w + c_a$ for $r > R_s$. In the downstream region the propagation directions of the scattering waves are assumed to be isotropized and $w' = w$.

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 at which the medium speed relative to the shock front $u = V_s - w$ undergo a jump from the value u_1 at $r = R_s + 0$ to $u_2 = u_1/\sigma$ at $r = R_s - 0$, where

$$\sigma = 4/(1 + 3/M^2)$$

is the shock compression ratio, $M = u_1/c_{s1}$ is the Mach number, c_s is the sound speed.

The phenomenological source term in the transport equation

$$Q = \left[u_1 N_{inj}/(4\pi p_{inj}^2)\right] \delta(p - p_{inj}) \delta(r - R_s)$$

describes the injection of some part $\eta = N_{inj}/N_1$ of medium particles N_1 into the acceleration process; $p_{inj} = \lambda m c_{s2}$ is momentum of injected particles. As usually we use the value $\lambda = 4$ here. We assume that the acceleration process starts at some distance r_0, which was taken $r_0 = 1.01 R_\odot$, where $R_\odot$ is the solar radius. As in the previous papers (Lee and Ryan, 1986; Berezhko et al., 1998) we assume high level of turbulence behind the shock, that provides negligible particle diffusion in the downstream region.

Particle diffusion coefficient is determined by the expression

$$\kappa = \frac{v^2 B^2}{32\pi^2 \omega_B E\left(k = \rho_B^{-1}\right)},$$

where $\rho_B = v/\omega_B$ is gyroradius; $\omega_B = eB/mc$ is the gyrofrequency; m , e and v are mass, charge and speed of proton; c is the speed of light;

$$E(k) = d(\delta B^2/8\pi)/d \ln k$$

is the energy density of Alfvén waves with a wave number k.

The background Alfvén wave spectrum 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 edge of the corona $r = R_\odot$. We use the results of statistical studies of Faraday rotation fluctuations, performed for heliocentric distances between 3 and 34 $R_\odot$, in order to estimate required values of β and δ. According to Andreev et al. (1997) spectral index of coronal Alfvén wave turbulence lies within the range $\beta = 1 \div 2$ with average value 1.5 and radial dependence is characterized by $\delta \approx 8$. We use these values $\beta = 1.5$ and $\delta = 8$ in our calculations below.

The value of wave number k_0 can be roughly estimated from the fact that typical upper SEP energy is of the order of 100 MeV. Assuming that this fact is related with the background Alfvén wave spectrum one can conclude that lowest wave number corresponds to the proton momentum $p \approx 0.5 mc$, that gives $k_0 = 3.6 \times 10^{-7}$ cm^{-1} if we take the large scale magnetic field near the Sun surface $B_* = 2.3$ G.

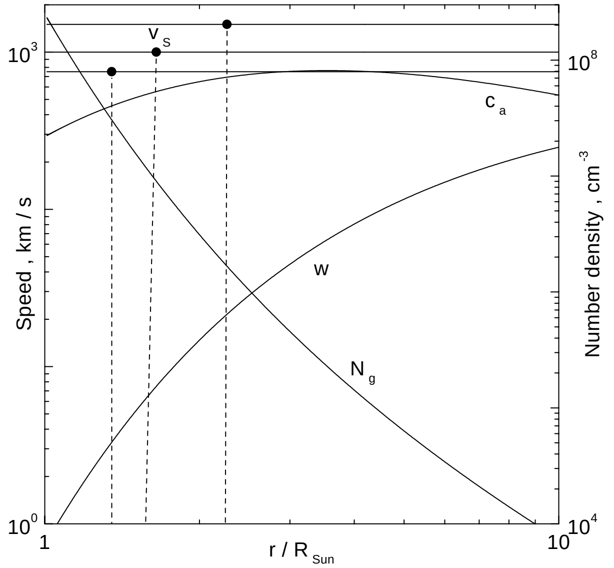

Fig. 1. Solar wind (w), Alfvén wave (c_a) and shock (V_s) speeds and gas number density N_g as a function of heliocentric distance. Vertical dashed lines shows the position of the shock where it becomes inefficient accelerator.

The amplitude of Alfvén wave spectrum E_0 can be derived from the fact that the energy flux of Alfvén waves $F_w \sim 10^5$ erg cm^{-2} s^{-1} is considered to be the main source of solar wind energy (e.g. Sittler and Guhathakurta, 1999). Therefore we can write $E_0 = \beta F_w/(2c_a) = 2.5 \times 10^{-3}$ erg/cm^3, where $c_a = 300$ km/s was taken for the corona base. At the moment it is not clear which part of the total Alfvén wave energy is contained in the range of frequensies $10 \div 10^3$ Hz cyclotron resonant with the protons of considered energies $10^3 \div 10^8$ eV. The value $E_0 = 10^{-3}$ erg/cm^3, which is used in our calculations below, is required to provide proton acceleration up to the energy $\epsilon_{max} \sim 100$ MeV.

We consider here acceleration process in a linear approach not taking into account Alfvén wave generation due to accelerated particle streaming instability. As it was shown for the case of interplanetary shocks selfexcited Alfvén waves do not influence essentially the spectrum of accelerated particles (Berezhko et al., 1998). In addition the 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 Sittler and Guhathakurta (1999) model for the corona gas density radial distribution $\rho(r)$. Gas speed w is determined from the continuity mass flux condition

$$w(r) = w_e [N_g(r)]/N_{ge}] (r/r_e)^2,$$

where $N_g = \rho/m$ is the gas number density and its value at the Earth's orbit is $N_{ge} = 7$ cm^{-3}.

Magnetic field radial dependence consistent with this model is described by simple formula

$$B = B_*(R_\odot/r)^2.$$

3 Results and discussion

We present in Fig.1 Alfvénic, solar wind and shock speeds and the corona number density as a function of heliocentric distance. Unfortunately the temporal evolution of the shock speed V_s is not very well known. Therefore we use the most simple case of constant speed V_s taking into account that the efficient SEP acceleration in our model takes place only during the initial relatively short period, corresponding $r < 3R_\odot$. One can see that solar wind and Alfvénic speeds are increasing functions of distance r at $r < 5R_\odot$. Since both of them are directed out of the Sun the effective shock compression ratio

$$\sigma' = u_1'/u_2 = \sigma(1 - 1/M_a),$$

where $u_1' = u_1 - c_a$, decreases during the shock propagation in this region due to decrease of M_a and the spectrum of accelerated particles becomes progressively steeper so that at some stage the contribution of freshly injected and accelerated particles in the overall spectrum becomes negligible. It is one of the most important factor which restricts period of SEP spectrum formation.

Fig.2 illustrates the behavior of accelerated particle spectrum during the shock propagation in the corona. We present there the differential (with respect to the kinetic energy ϵ_k) intensity of accelerated protons at the shock front

$$J = p^2 f(r = R_s, p, t)$$

for four subsequent evolutionary phases. Calculations correspond to the moderate injection rate $\eta = 10^{-4}$ and the shock speed $V_s = 1500$ km/s.

One can see that at early phases when $R_s < 2R_\odot$ the maximum accelerated particle energy, which separates the power law part of the spectrum from exponential turnover, quickly increases with time up to $\epsilon_{max} \sim 0.1$ GeV. Power law part $J \propto \epsilon_k^{-\gamma}$ (at nonrelativistic energies $\gamma = (q-2)/2$) corresponds to the universal spectrum of shock accelerated particles

$$f \propto p^{-q}, \quad q = 3\sigma'(\sigma' - 1),$$

where power law index q in the considered case gradually increases from 4.3 at $R_s = 1.1R_\odot$ to 5.5 at $R = 2R_\odot$ due to increase of Alfvén wave and wind speeds.

At later phases $R_s > 2R_\odot$ the spectrum shape becomes more complicated. Low energy part ($\epsilon_k < 1$ MeV) consisted of freshly accelerated particles still has a power law form. It becomes progressively steeper due to decreasing of the effective shock compression ratio σ' that continues up to $R_s = 5R_\odot$. High energy part of the spectrum ($\epsilon_k > 1$ MeV which

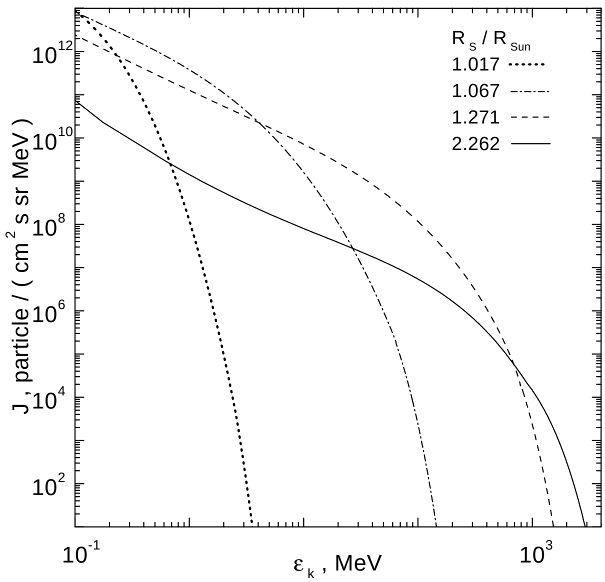

Fig. 2. Accelerated particle intensity at the shock front as function of kinetic energy for four subsequent phases.

is essentially harder consists of particles accelerated at the previous stages. The shock becomes to weak for these high energy particles and it does not any more efficiently accelerate them. These particles almost freely diffusively expends into the outer space with effective speed which is higher than the shock speed V_s. These effect of particle escape from the shock vicinity was initially described in modeling of the supernova shock evolution (Berezhko et al., 1996). Besides the steepening of accelerated particle spectrum there is other factor relevant for the particle escape. Particle escape takes place at energies for which so called modulation parameter

$$g = R_s V_s/\kappa(\epsilon_k)$$

is of the order or grater than unity (Berezhko, 1996). This may happen either due to decrease of $R_s V_s$ or due to increase of κ during the shock evolution. Second possibility takes place in the considered case. Modulation parameter deccreases during the shock propagation within the range $r = 1 \div 4R_\odot$ due to increasing of the particle diffusion coefficient

$$\kappa \propto B/E \propto r^{\delta-2-2\beta} = r^3.$$

Thus due to the specific distribution of coronal parameters the most efficient energetic particles production takes place during the initial relatively short period (about ten minutes) of shock propagation. Then according to our results these particles, at least the most energetic part of them, can be considered as freely propagated in the outer interplanetary space without any significant influence of the shock. One can use standard approach to describe propagation of these particles released from the source (i.e. from the shock vicinity) in order to reproduce the expected time profile of SEP event near the distinct observer.

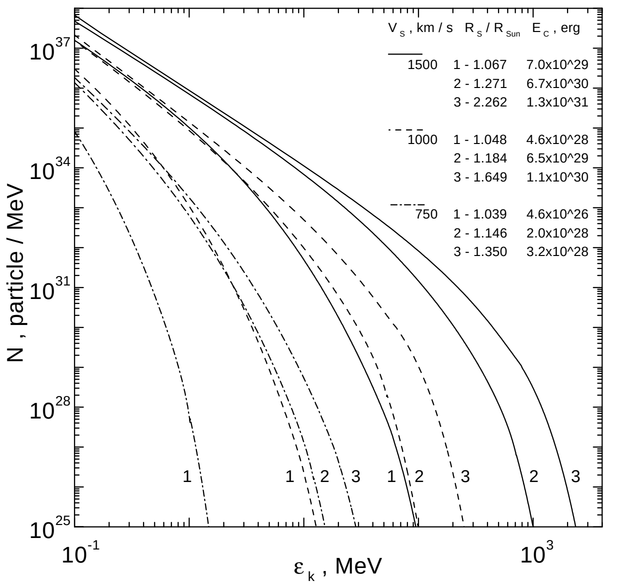

Fig. 3. Overall accelerated particle spectra as a function of kinetic energy for three values of the shock speed at three subsequent evolutionary phases.

Note that at larger distances $r > 5R_\odot$ the shock acceleration efficiency starts to increase again so that at $r \sim 1$ AU it typically generates particles up to the energy $\epsilon_{max} \sim 1$ MeV if the shock speed does not decrease significantly. Therefore at large distances $r \gg 5R_\odot$ the observed SEP intensity-time profile usually contains two peaks. The first one corresponds to the arrival of the main part of particles accelerated during the shock propagation in the corona and the second, which coincides with the shock, consists of particles injected and accelerated by the shock near the observer. Usually the upper energy of the second particle population is essentially lower than of the first one.

To calculate the expected SEP flux at large distances $r \gg 5R_\odot$ one need to know the overall accelerated particle spectrum

$$N(\epsilon_k) = \frac{4\pi p^2}{v} \int f(r,p,t) dV,$$

calculated at the moment of time when the shock becomes inefficient accelerator. Integration in this expression includes the whole volume V occupied by accelerated particles. We suggest that efficient acceleration takes place on 25% of the spherical shock front. Overall spectra calculated for the above case and for two other cases corresponded to the shock speeds 1000 km/s and 750 km/s are presented in Fig.3. Each of them consists of two different parts: power law and exponential turnover. Since the effective shock compression ratio is decreasing function of the shock speed power law index is smaller for higher shock speed: $\gamma' = 2$, 2.2 and 2.8 for $V_s = 1500$, 1000 and 750 km/s respectively. Cutoff energy ϵ_{max} restricted the power law part of the spectrum can be defined as a point where

$$d \ln N / d \ln \epsilon_k = -\gamma' - 1.$$

Then the overall spectrum can be represented in the form

$$N(\epsilon_k) \propto \epsilon_k^{-\gamma'} \exp\left[-\left(\epsilon_k/\epsilon_{max}\right)^\alpha / \alpha\right],$$

where at nonrelativistic energies $\alpha = (2-\beta)/2$. The most impressive point is that the value of the cutoff energy is very sensitive to the shock speed value: $\epsilon_{max} \approx 100$ MeV at $V_s = 1500$ km/s and it drops by an order of magnitude if the shock speed decreases by a factor of 2. As a consequence the total energy content E_c of accelerated particles with energies $\epsilon_k > 0.1$ MeV has a similar dependence upon the shock speed (see Fig.3). This strong dependence of $N(\epsilon_k)$ and E_c on V_s is a consequence of the fact that the range of heliocentric distances where efficient acceleration takes place essentially depends on the shock speed V_s (see Fig.1). This qualitatively agrees with the observed strong positive correlation between peak SEP intensity and shock speed as well as the strong positive correlation between SEP intensity and the cutoff energy, which is called also as a knee energy (Reames, 2000).

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 sufficiently efficient acceleration in solar corona within the range of heliocentric distances $r < 3R_\odot$.

Performed calculations show that the shock generated particle spectra have the spectral form and energy content consistent with observational properties of SEP events.

Calculations revealed a strong dependence of MeV particle intensity and their cutoff energy upon the shock speed, that is at least in qualitative agreement with the experiments.

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