Joint acceleration mechanisms for solar cosmic rays

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Abstract. Using Monte Carlo method we have simulated solar cosmic ray spectra ($^3$He, $^4$He, O and Fe) at the flare site and at the Earth. It is shown that besides stochastic acceleration by Alfvénic turbulence an impulsive electric field of the current sheet significantly affects the ion energy spectra at low energies. Both mechanisms could explain some peculiarities in the energy spectra of heavy ions observed in experiments onboard ACE.

1. Introduction

Our previous paper has dealt with the modelling of energy spectra of heavy ions ($^3$He, $^4$He, O and Fe) accelerated in impulsive SEP event of October 5, 2002. These spectra are characterized by deep depletions in the energy range 0.2-0.7 MeV/nucleon measured on ACE. As was shown earlier, they could be a sign of the energetic ion deceleration due to their interaction with ambient plasma [1-3]. At typical temperatures $T\sim10^6-10^7$ K the Coulomb interaction for different energetic ions has a maximum at energies $E_{\text{max},e}\sim0.4-4$ MeV/nucleon. One may expect slight shifting of these peculiarities to lower energies because of the subsequent adiabatic losses in the interplanetary space.

Our recent numerical analysis [4], taking into account Coulomb interactions and stochastic (second order Fermi) acceleration of heavy ions for SEP event of October 5, 2012, has shown that 1) the Coulomb losses cannot result in the observed spectra peculiarities simultaneously for helium isotopes and heavier ions; 2) at low energies ($<0.4$ MeV/nucleon) the differences between theoretical and experimental spectra stay significant if we assume similar (or very close) acceleration conditions for all ions under consideration; 3) long-lasting propagation of ions in the interplanetary space cannot fit the low energy part of the spectra at relevant parameters of the interplanetary space as well.

In [5] there was explored the possibility to account for the deeps mentioned above (for $^3$He and $^4$He only) on the assumption of a broken power-law spectra for accelerating plasma waves. Here we suggest another explanation with one more process affecting the energy spectra at low energies included into consideration. This low energy part could be prescribed to the current sheet acceleration though at high energies these spectra can successfully be fitted in the framework of stochastic acceleration mechanism only. Simulations of energy spectra of protons in electric field of the current sheet and in turbulent motions, applying to the impulsive events, were carried out in a number of papers (see, e.g., [6, 7]). As a rule, these mechanisms operate separately without any mutual influence.

However it is known (also from observations) that both mechanisms can operate in the flare regions simultaneously [8]. In the paper [9] for the SEP event in question a plasma jet was observed. Such jets are typical for impulsive events and are the signatures of the magnetic flux redistribution in flare regions, i.e. are the markers of the magnetic reconnection and, hence, powerful electric field existence.
2. Parameters of the model and results

Rather numerous literatures are devoted to the simulations of the particle energy spectra in solar flares. Majority of them deals with stochastic or regular mechanisms (by electric field or by shock wave) as the only one operating in the flare site. Particularly, in [7] the acceleration of protons at their motion along $\sim 10^9$ cm X-line with magnetic field $B \sim 300$ G and electric field $\sim 30$ V/m was considered allowing one to generate relativistic particles up to $10^{12}$ eV. As to the spectra forms, various authors have obtained both power-law [10] and exponential [7] spectra.

Our approach implies 1) significantly smaller magnitudes of the electric field and current sheet length than in [7] because for relatively weak impulsive flares we need to accelerate particles up to $\sim 10$ MeV/nucleon; 2) simultaneous operating both stochastic and electric field acceleration mechanisms; 3) spatial diffusion of particles in the whole acceleration (and propagation) region. Knowing the character of particle motion in the vicinity of a current sheet [11] we simplify our modelling to 2D simulations.

The simplest scheme of the current sheet used in our simulations is the following (see figure 1): the plasma drifts with the velocity $V_{in}$ (where $|V_{in}| \sim V_A(B_1)$) to the sheet localized within the interval $[-XL/2\eta, XL/2\eta]$. The electric field $E$ is parallel to the Z axis, and the plasma flows out the current sheet with the drift velocity $V_{out}$ dependent on $B_2$. Analytic consideration of the problem [8, 11] shows that the regular ion energy gain takes place mainly along the Z axis, while the movement along Y coordinate is finite (within several Larmor radii). As a result, the $V_y$ component of the particle velocity increases with time slower than $V_z$ component. Since it is more important for us to obtain the particle energy spectra than their accurate trajectories one can exclude Y coordinate from our consideration.

![Figure 1. The scheme of the current sheet.](image)

We make use the Monte-Carlo method to simulate ion energy spectra as in our previous papers [2-4, 6]. The particle injection with the energy $E_{inj}=100$ eV/nucleon takes place at $t=0$ uniformly in the interval $[-XL/2, XL/2]$ along the boundary $Z=0$. In the current sheet region the particle is accelerated by the regular electric field $E$ and also by the fluctuations of the turbulent background plasma. Notice that some particles cannot reach the current sheet at all (if their initial coordinate $|x|>XL/2\eta$) or may rapidly leave this layer (due to spatial diffusion). The contribution of these particles to the resulting energy spectra is determined by the stochastic acceleration only. Furthermore, the particle can leave the current sheet if it crosses the boundary $Z=ZL$ (the end of the neutral line) or the boundaries $x=\pm XL/2\eta$ as a result of the random walk and/or directed convection with the velocity $V_{out}$. Leaving the current sheet the particle continues its stochastic acceleration. Finally it leaves the acceleration process crossing the boundaries $x=-XL/2$ (to the Sun) and $x=XL/2$ (to the Earth).

In our simulations we propose the following parameters set: $XL\sim ZL\sim 10^7$ km; $B_1\sim 30$ G; $E \sim 7$ V/m; $\eta=5$; $V_{out}\sim 10^7$ km/s; $T\sim 10^7$ K; $N\sim 10^{11}$ cm$^{-3}$. The spatial and energy diffusion coefficients are dependent on energy and charge in the same way as it was assumed in [4, 6].
On figure 2 one can see the typical shape of the energy spectra of ions ($^4$He as an example) accelerated by both stochastic and regular mechanisms simultaneously. Our modelling allows us to conclude that the spectra at low energies (domain I) is mainly determined by the energy diffusion coefficient outside the current sheet. This energy region is formed by the particles not reached the current sheet or (when reaching) rapidly carried away due to spatial diffusion and/or convection. The spectra at these energies do not significantly depend on the magnitude of the electric field E while the "length" of the domain II in the spectra is specifically determined by E.

If the acceleration region coincides with the current sheet ($\eta = 1$) the low energy part of the spectra contains not so many particles. They are those being close to the boundary and being convected out the acceleration region. The domain III of the spectra is a result of pure stochastic acceleration outside the current sheet, i.e. after the (regular + stochastic) acceleration inside it. So, for this part of the spectra the current sheet plays the role of pre-accelerator.

Our modelling also takes into account the possibility for heavy ions (Fe and O) to change its charge due to stripping effects similar to the charge-consistent acceleration models [6]. Clearly, these effects are mainly important for Fe and in a lesser degree for O. Since the ion initial charge $Q_0$ in the acceleration regime depends on temperature the subsequent behaviour of the mean charge with energy, $Q(E)$, also depends on temperature.

![Figure 2. Typical energy spectra of ions ($^4$He as an example) accelerated by turbulence and by electric field E of the current sheet.](image)

As to the spectra for the event of October 5, 2002, the stochastic acceleration inside the current sheet does not apparently play an important role. For this event the characteristic acceleration times for both mechanisms differ by one order of magnitude (~0.1 s and ~1 s, respectively). It really affects the spectra of ions being accelerated stochastically outside the current sheet. Typical values for the spatial diffusion coefficients are $D \approx 10^{16}$ cm$^2$/s at 1 MeV/nucleon with the energy dependence $\sim E^{3/4}$ (for the power law index of turbulence $S=1.5$). The decrease of the diffusion coefficient in the current sheet results in the much longer E action on particles. Hence, in this case they gain much more energy. The spectra modification for the D decrease is almost equivalent to the case of E increase.

Using the model described in this Section we tried to fit more carefully the spectra for the SEP event of October 5, 2002, in the low energy domain as well (see figure 3). One should stress that all ion spectra could be fitted making use the same parameters of the acceleration region (see above).
Figure 3. Energy spectra of ions (³He, ⁴He, O and Fe) for the SEP event of October 5, 2002. Symbols are the measurements on ACE; lines are the numerical fits to the data. On the figures with ion spectra the vertical axes are in arbitrary units.

3. Conclusions
In this Section we briefly outline the results of our simulations. Of course, account in our modelling one more mechanism of particle energy gain adds some new parameters in comparison with the case of a single mechanism. However, the existence of the current sheets is the experimental fact not only for different astrophysical conditions with the magnetic field reconnection but also for laboratory plasma. Also, the astrophysical medium is rather turbulent than laminar. This particularly refers to the solar flare plasma. Therefore, we suppose that our approach has deep experimental basis. All this in turn results in a great variety of theoretical spectra of ions allowing one to fit successfully experimentally observed spectra at low energies. Importantly, in the framework of our modelling we succeeded to fit spectra of all ions approximately at the same plasma parameters (same acceleration regions for different ions). It is also important for heavy ions to fit (in addition to their energy spectra) the dependence of the mean charge (or higher moments of the charge distribution function) with energy, Q(E). Unfortunately, we have no such data for the considered event.

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