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Different Types of Plasma Turbulence in the Process of Solar Particle Acceleration

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Abstract. Within the frame of solar cosmic ray (SCR) energy spectra, we present the results of a study of different kinds of turbulence that presumably can co-exist at the Sun in the sources of accelerated particles. On basis of a two-source model of particle generation, one of which is associated with an expanding magnetic loop, we applied the transport equation including adiabatic losses simultaneously with the stochastic acceleration process. Observations show that there are two different populations during some SCR events. One of them, the so-called "Delayed Component" (DC), may be correctly described by stochastic acceleration. The second one, the so-called "Prompt Component" (PC) seems to be described by the deterministic acceleration process in large-scale coronal structures (magnetic neutral current sheets). Co-lateral inferences are obtained for a series of large solar events (29 September 1989, 14 July 2000, 15 April 2001, 28 October and 2 November 2003, and 20 January 2005). We found that the required acceleration efficiencies turned out to be very high, so that for the events of 28 October 2003 and 20 January 2005, adiabatic cooling is negligible. Qualitative inferences point toward a dominated Alfvén turbulence, at least, during the events of 28 October 2003. Our results also provide a new support to the existence of two relativistic particle populations in some SCR events.

Keywords: Space plasma, Sun, solar flare, plasma turbulence, particle acceleration, large scale coronal structures
PACS: Category 90, Geophysics, Astronomy and Astrophysics

INTRODUCTION

It has been recognized long ago that in any location, either at the laboratory or astro-geophysical scales, whenever plasma turbulence is established, it becomes the site of particle acceleration. The accelerating agents, ultimately, are electric fields, the phenomenological conditions, however, may strongly vary from laboratory to astrophysical scenarios. In some cases space plasma research has made the keystone contribution to basic plasma physics, in others, the dominant contribution has been made by laboratory plasma experiments.

Sounding space sources of particle acceleration can be made through the analysis of emitted radiation from the interaction of accelerated particles with matter and electromagnetic fields, or by the study of the properties of the accelerated particles themselves. The distribution of particles according to their energies (energy spectrum), is one of those properties. The study of such spectra in the sources allows inferring about the kinds of acceleration mechanisms, involved of turbulence, parameters of the acceleration process and local physical parameters (magnetic field strength, plasma density and temperature). Below we concentrate on the source spectra of solar energetic particles (SEP) [1], or solar cosmic rays (SCR) [2].

Some years ago the authors [3] have succeeded to derive an analytical expression for the whole time-dependent energy spectrum of stochastically accelerated particles. That was done by solving the momentum-diffusion equation by means of the WKBJ method. Below we summarize our earlier results [4-11] obtained for some SEP events. The main attention is paid to the recent super-event of 20 January 2005.

MODEL OF STOCHASTIC ACCELERATION

The particular case of particle acceleration in space plasmas is focused on two interdependent aspects, the small-scale and large-scale behaviors (or microscopic

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and macroscopic processes, respectively). Since 1992 we have studied [4-11] different kinds of turbulence that presumably can co-exist at the Sun in the sources of SEPs: the MHD modes (slow, fast and Alfvén ones), Langmuir and Bernstein waves. We delimitated the efficiency of such kind of turbulence on basis to their survival time to dissipation processes and their ability to reproduce the observed SEP spectra.

The formalism of stochastic acceleration model [3] is based on the very well known kinetic approach of a momentum-diffusion equation in the phase space for the pitch angle-averaged particle density. Under a variable change it can be transformed to a generalized Fokker-Planck type equation. By the WKBJ method, the analytical time dependent solution, through all the energy ranges (non-relativistic, transrelativistic, and ultrarelativistic ones) was obtained [3]. Within the concept of two RSP sources (e.g., [2, 6], where one of them is associated with an expanding magnetic loop, we later have solved [10] the transport equation (by the same method) with including adiabatic losses in the systematic energy change rate, simultaneously with the stochastic acceleration process.

We applied then our model to the relativistic solar particles (RSP), or to so-called Ground Level Events (GLE), observed by ground-based neutron monitors (NM), specifically those which present two RSP populations, prompt and delayed ones (PC and DC). The plausible source and acceleration parameters for some GLEs of the 22-23 solar cycles were derived in [4-11] from the confrontation of theoretical spectra [3, 10] with observed ones for both components: the DC vs. stochastic acceleration and the PC vs. deterministic acceleration.

Typical scenario for such kind of events was developed in terms of two different sources for prompt and delayed particle populations (e.g., [2, 6]). The PC is assumingly produced by a deterministic process in a magnetic neutral current sheet high in the corona (in a region of open field lines). As to the DC, the bulk of particles are stochastically accelerated in the flare body, within an expanding closed magnetic structure in the low corona. Here we limit our study to the DC of the GLE of 20 January 2005.

This event was related to the flare occurred in the well-connected region at the Sun. So, in principle, effects of azimuthal propagation for RSP may be ignored. Up to now, in the derivation of the time-dependent spectrum, we have assumed that particle acceleration in the GLEs is so efficient that, in the first approximation, we could ignore energy losses during the acceleration process itself. However, it should take into account that this phase acceleration occurs within expanding plasma. In addition, these kinds of events occur in association with Coronal Mass Ejections (CME) and CME-driven shock waves (e.g., [12]). So, we analyse below the possibility that adiabatic cooling during the acceleration process in the expanding plasma could have some effect on the spectrum.

SUPER-EVENT OF 20 JANUARY 2005

A super-GLE No.69 of 20 January 2005 turned out to be the greatest one since 23 February 1956. The parent solar flare 2B/X7.1 had heliocoordinates 14°N, 61°W. Some characteristics of SEPs by the data of by NM, balloon and spacecraft observations have been reported in 15 papers at the 29th International Conference on Cosmic Rays (e.g., [12-15]) (for more details see http://icrc2005.tifr.res.in/). Also, there were analyzed some related topics, in particular, the relation between the GLEs and CMEs. In this particular event, a CME speed was estimated to be ≈ 3675 km/s [12].

The data of 32 NMs, including two new opened stations Barentsburg (N78°.08, E14°.12, Spitsbergen) and Baksan (N43°.28, E42°.69) at the Baksan Neutrino Observatory (BNO), North Caucasus, Russia, as well as the balloon measurements were analyzed in two papers [13, 14]. For the first time, in [14] the data of the BNO EAS Arrays "Carpet" (200 m^2, 1700 m above sea level) and "Andyrchi" (37 m^2, 2050 m a.s.l.), as well as the Baksan Muon Detector (BMD, 190 m^2) data [15] were used in this kind of analysis. These instruments have the better sensitivity to SCR than that of standard NM at geomagnetic cutoff ~ 6 GV. Figure 1 shows energy spectra of RSP derived by NM data at different times (1- 07:00 UT, Flux 1; 2 – 07:00 UT, Flux 2; 3 – 08:00 UT), together with direct GOES-11 and balloon measurements [14].

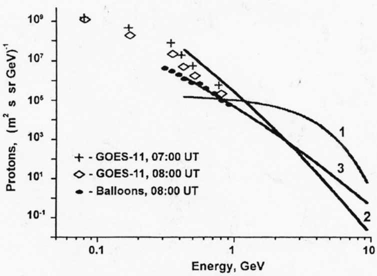

FIGURE 1. Derived energy spectra at different times of the event of 20 January 2005 (1- 07:00 UT, Flux 1; 2 – 07:00 UT, Flux 2; 3 – 08:00 UT), together with direct GOES-11 (crosses and open rhombi) and balloon data (black rhombi).

An optimization method [9] was applied to the above data to obtain some parameters of RSP, in particular, their energy spectra. The authors [14] used the data of NMs at Apatity (APTY), Barentsburg (BRBG), Yakutsk (YKTK), McMurdo (MCMD), South Pole (SOPO), and EAS Array at BNO (Carpet) [15], integral proton fluxes from >150 to >400 MeV as measured in the stratosphere above Apatity [13], and intensity time profiles obtained by the GOES-11 spacecraft at energies from >10 to >100 MeV.

As it was noted long ago (e.g., [16, 17]), using the integral energy spectrum of accelerated solar particles, derived by the values of maximum intensity near the Earth orbit observed above given energy at the Earth's orbit, we obtain a proxy of the source spectrum, especially for the well-connected events (time-of-maximum, or TOM, method), just as a case of the event under consideration.

RESULTS AND DISCUSSION

The GLE of 20 January 2005 seems to have two RSP components [14]. In our theoretical modeling below we use the spectrum of the DC (curve 2 in Figure 1). Figure 2 represents the best fitting to the observations for the spectrum of DC. Our calculations were based on the two equations [10], considering and ignoring adiabatic losses. The first one corresponds to the case of pure acceleration with acceleration rate $\alpha(t)$ with no energy losses ($\rho = 0$), whereas the second equation corresponds to a finite value of ρ. In fact, $\rho(t)$ and α(t) are both time functions; however, ρ has been predetermined by assuming an expansion velocity about 3675 km/s [12]. Hence, the only real free parameter is $\alpha(t)$. Finally, we used a following set of parameters: acceleration efficiency $\alpha = 0.05$ s^{-1}, the mean confinement time $\tau = 1.0$ s, the elapsed acceleration time $t = 1.0$ s, the rate of adiabatic cooling $\rho = 0.012$ s^{-1}, and the injection energy $E_0 = 1.0$ MeV.

The obtained results can be summarized as follows: 1) rather high acceleration efficiency ($\alpha \geq 0.05$ s^{-1}) is needed in order to obtain a good fitting of the data; 2) for such efficiency value, the term of adiabatic deceleration has practically no contribution. That avoids us to infer whether there was or not a plasma-expanding phenomenon, such as a CME-driven shock wave, simultaneously with the stochastic acceleration stage.

Within the frame of proposed scenario (e.g., [2, 6]), we assumed that the DC is generated into a closed expanding magnetic structure by fast mode turbulence. In the course of such an expansion this structure gets in touch with other loops, one of which may be of opposite polarity, creating a magnetic neutral current sheet. Local particles in the sheet diffusion region are impulsively accelerated [2, 6] by the deterministic electric fields produced in the process of magnetic reconnection. These particles are seen at the Earth as the PC around 07:00 UT (curve 1 in Figure 2).

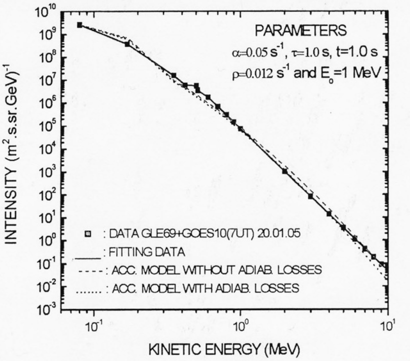

FIGURE 2. Fitting of the source energy spectrum of DC by the data of NM and GOES-11 observations at 07:00 UT of 20 January 2005 (black squares), considering and ignoring adiabatic losses (blue and red lines, respectively).

It must be emphasized that we could not predict in advance that adiabatic cooling would have not any noticeable effect, because we do ignore the values of our free parameter α. It is just at the moment of doing the best fits that we found that the required α values are practically the same in both cases, even though the spectra are slightly distinguishable.

If the derived values of α were of the order of ~ 0.01-0.001 s^{-1}, as we have found for the 14 July 2000 and 15 April 2001 GLEs, the effect of adiabatic cooling would not be negligible. On the other hand, in the event of 28 October 2003 the experimental spectra are very flat [10], so that the stochastic acceleration requires of very high acceleration efficiency (between 0.65 and 0.9 s^{-1}) to reproduce them. It cannot be excluded that the predominant turbulence involved in the acceleration of particles in this event may differ from the predominant one in other events.

The study of acceleration efficiencies shows that acceleration by short wave turbulence (Bernstein modes) may be higher than other longitudinal waves as Langmuir turbulence. This is a promising process in the non-relativistic particle domain but not for RSP. Besides, due to mass motions, magnetic reconnection and instabilities of macroscopic magnetized systems in flare plasma, the presence of MHD seems highly probable (as a review see, e.g., [8]).

Slow magnetosonic mode of MHD turbulence may be an interesting option to accelerate particles from the thermal background at chromospheric levels [4], but in the coronal plasma it requires of a continuous source of turbulence at a rate $\geq 10^3$ erg/cm^3.

The same requirement of turbulent energy density is needed for resonant interaction particle-Alfvén MHD mode, but in this case the acceleration is only efficient for particles with initial velocities much higher than the local hydromagnetic velocity. The less restricted turbulence to accelerate solar particles and to fit observational constraints seems to be the fast MHD mode. A simplified approach to the problem of turbulent energy supply ignoring non-linear wave-wave interactions and cascade effects, assuming a constant and steady injection rate of turbulence with a mean life time of about 1 s was carried out in [8] with consideration of wave energy dissipation and Coulomb particle energy losses. It was found that protons can be accelerated up to energies > 1 GeV in a time t < 1 s. The steady situation of the acceleration process is reached after 5-60 s [8], which explains the invariability of DC spectra slope after some time.

CONCLUSIONS

We have shown that for the GLE of 20 January 2005 the adiabatic deceleration is negligible with respect to the acceleration, because the adiabatic deceleration rate is about 5 times lower than the acceleration rate, even that expansion velocity about 3675 km/s was higher than in other events. Also, the acceleration efficiency for this event turned out to be rather high. It does not mean, however, that the Alfvén mode may have prevailed during this event. At the same time, the Alfvén waves have a longer mean life time than the other two MHD modes, because they are more resistant to the several dissipation processes that affect them in the turbulent regions of solar flares.

Probably, the most important conclusion is that the DC in this particular event can be in a straight way explained by spectra from stochastic acceleration, what cannot be done for the PC. This result effectively points toward the confirmation of two components of different origin indicating the existence of two relativistic particle populations in some SRP events.

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