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Relativistic proton production at the Sun in the 20 January 2005 solar event

Jorge A. Pérez-Peraza [a], Eduard V. Vashenyuk [b,*], Apolonio Gallegos-Cruz [c], Yurii V. Balabin [b], Leonty I. Miroshnichenko [a,d]

[a] Instituto de Geofísica, Universidad Nacional Autónoma de Mexico, CU, Coyoacán, México, DF 04510, Mexico
[b] Polar Geophysical Institute, Cosmic Ray Group, Fersman Street 14, 184209 Apatity, Murmansk Region, Russia
[c] UPIICSA, IPN, Depto. de Ciencias Básicas, Té 950, Iztacalco, México, DF 08400, Mexico
[d] N.V. Pushkov Institute IZMIRAN, Russian Academy of Sciences, 142190 Troitsk, Moscow Region, Russia

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Abstract

Based on the concept of multiple acceleration of solar energetic particles (SEP) we analyzed the super-event of 20 January 2005 by the data of ground level, balloon and spacecraft observations. The main characteristics of relativistic solar protons (energy spectra, anisotropy directions and pitch-angle distributions) are derived and their dynamics during the event is studied. It is shown that the flux of relativistic solar protons may consist of two distinct components, the so-called prompt and delayed ones. Within a two-source model of particle generation, one of which is associated with an expanding magnetic loop, we solved the transport equation in energy phase space, including adiabatic losses simultaneously with the stochastic acceleration process, and calculate the expected spectra of the delayed component at the source. The confrontation of experimental spectra with theoretical ones shows that the delayed component may be correctly described by stochastic acceleration, but not the prompt component. The required acceleration efficiencies turned out to be rather high, so that, for this particular event, adiabatic cooling is practically negligible. Our results provide a new support to the existence of two populations of relativistic solar protons in some SEP events.

Keywords: Sun; Solar flare; Solar cosmic rays; Particle acceleration; Large scale coronal structures

1. Introduction

The Sun episodically emits cosmic rays of sufficient high energy and intensity to increase radiation levels on the Earth's surface. Long ago, this kind of events was called Ground Level Enhancements (GLE) of solar cosmic rays (SCR) (e.g., Sakurai, 1974). Since the first GLE of 28 February 1942 (or GLE01 in modern classification) observed by ground-based ionization chambers, and up to the end of 2006, in total 70 such events have been registered. Systematic observations by neutron monitors (NM) began in the 1950's, and since then GLEs occur at a rate about 15 per solar cycle (Bieber et al., 2005). The largest of them is the famous 23 February 1956 event (GLE05).

During the GLE of 23 February 1956 radiation levels near sea level increased by as much as 47 times in some sites. Several additional giant GLEs were recorded in the pre-NM era, but until 20 January 2005 no event of giant amplitude (characterized by an increase of, say, 5 times or more in the sea level NM count rate at some locations) had been observed since 1956. Within a 6-min span on 20 January 2005, the count rate registered by NM at the sea level station McMurdo (Antarctica) increased by a factor of 30, while the rate at the high-altitude (2820 m) site of South Pole station increased by a factor 56. So, by the data of McMurdo NM this GLE No. 69 was the largest one observed at sea level since 1956 (e.g., Bieber et al., 2005).

* Corresponding author. Tel.: +7 815 557 9173; fax: +7 815 557 4339.
E-mail address: vashenyuk@pgi.kolasc.net.ru (E.V. Vashenyuk).

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On the other hand, some years ago the authors (e.g., Gallegos-Cruz and Pérez-Peraza, 1995) have succeeded to derive an analytical expression for the time-dependent energy spectrum in the whole energy range, assuming a stochastic process for SEP acceleration. Up to 1995, similar expression used to exist only in partial energy domains: non-relativistic (analytical solution), trans-relativistic (numerical derivation) and ultra-relativistic (analytical solution). Our derivation was done by solving analytically the momentum–diffusion equation by means of the Wentzel–Kramer–Brillouin–Jeffreys (WKBJ) method.

When applied to the production of solar energetic particles (SEPs), it was done for the case of relativistic solar proton events, or GLEs, specifically those which present two relativistic particle populations, prompt and delayed ones. From the comparison of theoretical spectra with observational ones for both components (the delayed component vs. stochastic acceleration and the prompt component vs. deterministic acceleration spectra) the plausible source and acceleration parameters for some events of the 22–23 solar cycles were derived (Miroshnichenko et al., 1996; Miroshnichenko, 2001; Pérez-Peraza et al., 2006). In Pérez-Peraza et al. (2006), a rate of energy loss by adiabatic cooling has been introduced into the transport equation. By comparing the calculated spectra with observed ones in the GLE of 28 October 2003 it was shown that the adiabatic deceleration is negligible with respect to the acceleration, because the adiabatic deceleration rate is ~1–2 orders of magnitude lower than the acceleration rate, which was relatively high.

In the present paper, we carry out an extended study to the GLE of 20 January 2005 based on the concept of multiple acceleration of SEPs, by the data of ground level, balloon and spacecraft observations (Vashenyuk et al., 2005a,b). Those data are described in Section 2, together with the method of their analysis. We also present the energy spectra of RSP derived from observations. Section 3 contains the main points of our two-source (two-component) approach to the GLE analysis. In Section 4, we describe the mathematical formalism of the stochastic acceleration used in this study. In Section 5, we apply our theoretical model to the delayed component of the GLE69 and discuss the results within the frame of two-source model of SCR production. Section 6 contains our main conclusions.

2. Observations

As mentioned before the super-GLE69 of 20 January 2005 was the greatest event of the last five decades. In Vashenyuk et al. (2005a), the parameters of relativistic solar protons in the GLE69 were obtained and their dynamics studied. Data of 32 neutron monitors (NM) as well as the balloon measurements were analyzed. The GLE was extremely anisotropic at the initial stage of the event as observed by the ground-based cosmic ray detectors (Fig. 1a). Balloon measurements of solar protons were carried out by Vashenyuk et al. (2005a) at a launching site in Apatity (Murmansk Region, Kola Peninsula, Russia).

The worldwide NM network may be considered as a united multidirectional solar proton spectrometer in the relativistic energy domain. By modeling the ground-based detectors responses to an anisotropic solar proton flux and comparing them with observations, the parameters and dynamic of primary solar protons outside the magnetosphere can be obtained by a least square technique (optimization method) (e.g., Shea and Smart, 1982; Cramp et al., 1997). The optimization method was applied to the GLE of 20 January 2005 (Vashenyuk et al., 2005b) to derive the parameters of RSP, namely, energy spectra (Fig. 1b and c), anisotropy directions and pitch-angle distributions.

It was found that the flux of relativistic solar protons consists of two components, namely hereafter, Flux 1 and Flux 2. In Fig. 1b and c, the energy spectra of multi-GeV protons are shown, in logarithmic and semi-logarithmic scales, respectively, as derived from ground-based NM observations at different times (Flux 1, 1 – 07:00 UT; Flux 2, 3 – 08:00 UT). Also, it is shown the direct GOES-11 data (crosses and open rhombi) and balloon measurements at Apatity (black circles). The spectra 1 and 2 correspond to Flux 1 and Flux 2 at 07:00 UT, when the strong anisotropy and intensity maximum were observed at South Pole and McMurdo stations. Spectrum 3 was derived for 08:00, after the maximum intensity in a period of weak anisotropy.

The spectra of the two fluxes at 07:00 UT strongly differ. The spectrum 1 flattens at its low-energy side and, as can be seen, has exponential dependence on energy. The spectrum 2 has a kind of power-law form and may be extended with the same slope into the high energy range (1000 of Mev), moderate energies (>400 MeV), and low energies (<100 MeV) as direct solar proton data obtained by the GOES-11 spacecraft and ballons show. The spectrum 3 also has a power-law form and extends into the moderate energy region.

To complete the observational picture of the GLE69, we show in Figs. 2 and 3 the maps of asymptotic directions for arrival of relativistic solar protons to the Earth at 07:00 UT, together with anisotropy axes, and corresponding pitch-angle grids for the Flux 1 and Flux 2, as well as the dynamics of their pitch-angle distributions. The symmetry axis of the Flux 1 passes through asymptotic cones of the South Pole and McMurdo stations that registered the maximum increases.

As one can see from Fig. 2, the Flux 1 was extremely anisotropic. In fact, the stations with asymptotic cones out of 30° limit (e.g., Thule, Fort Smith, Sanae, and Barentsburg) did not respond to the Flux 1 at all. The Flux 2, with a steep and power-law spectrum had the pitch-angle distribution wider than the Flux 1 (Fig. 3). Due to this feature, the Flux 2 caused an increase effect on the majority of NM stations during the anisotropy phase (up to 07:30 UT). It should be noted the large deviation (60°) of the symmetry axis of Flux 1 from a nominal direction of the interplan-

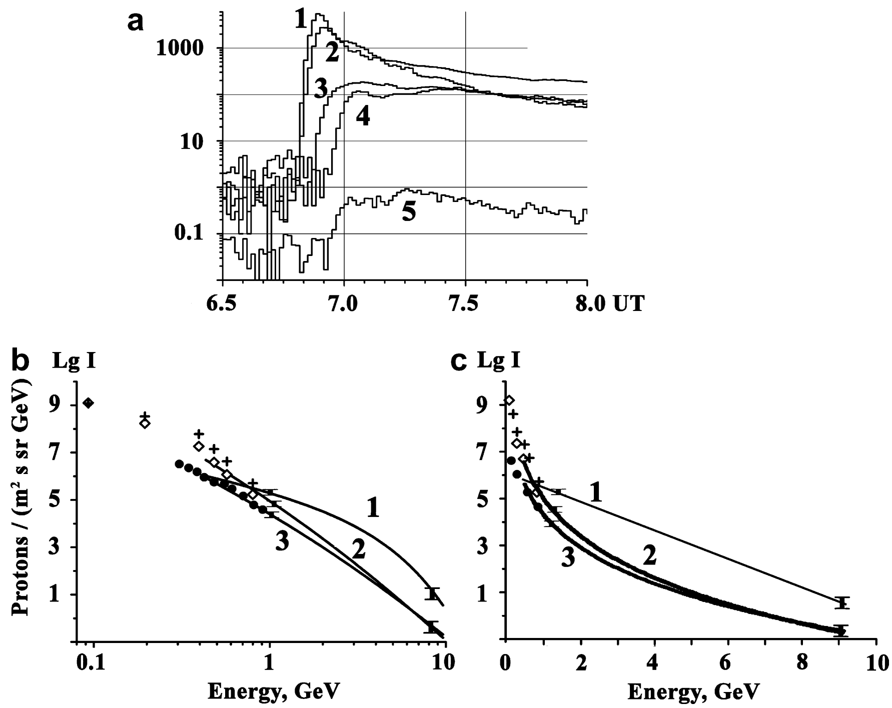

Fig. 1. (a) Increase time profiles of ground-based neutron monitors: South Pole (1), McMurdo (2), Apatity (3), Barentsburg, (4), and EAS Array "Carpet" at BNO (5); (b) derived energy spectra of the multi-GeV solar particle event of January 20, 2005 at two different times (1 – 07:00 UT, Flux 1; 2 – 07:00 UT, Flux 2; 3 – 08:00 UT, Flux 3) in the logarithmic scale, together with direct GOES-11 data (crosses and open rhombi) and balloon measurements at Apatity (black circles); (c) is the same as (b) in semi-logarithmic scale.

etary magnetic fields (IMF). The symmetry axis of the Flux 2 is more aligned with the IMF, and did not change notably its direction after 07:30 UT, when the Flux 1 has disappeared.

It was emphasized long ago (Miroshnichenko et al., 1974) that using the integral energy spectrum of accelerated solar particles, derived by the values of maximum intensity near the Earth orbit observed above a given energy at the Earth's orbit, we obtain a proxy of the source spectrum, especially for the well-connected SEP events. Some later, this methodical approach was called a time-of-maximum method, or TOM method (e.g., Forman et al., 1986).

3. Two-source approach

The scenario for the events with relativistic solar protons has been extensively discussed and summarized by the authors in previous works (e.g., Miroshnichenko et al., 1996; Pérez-Peraza, 1998; and Miroshnichenko, 2001). Here, we will limit to remind its basic features. It is based on two different sources of particle acceleration, the prompt component, whose acceleration is carried out by a deterministic process in a magnetic neutral current sheet (MNCS) high in the corona (in a region of open field lines), and the delayed component. With the previous synthesis of the results of Vashenyuk et al. (2005a,b) it is pretended to show here the presence of two different components in this event: a prompt (Flux 1) and a delayed one (Flux 2). In our theoretical modeling below we will concentrate on the spectrum of the delayed component that corresponds to Flux 2 (curves 2 in Fig. 1b and c).

Regarding the *source of the delayed component*, detailed studies of the time that particles spend in the corona indicates this time is energy-independent (all particles of all energy have the same coronal storage time before being ejected) points toward a source connected with a transient, in a closed magnetic structure (usually associated to a magnetic bottle). Therein, particles are accelerated stochastically in the flare body, within an expanding closed magnetic structure in the low corona, by the dissipation of local turbulence to a select number of particles able to undergo resonant interactions with the local turbulent wave modes.

So, it is proposed that the delayed component is generated in the flare volume, or its vicinity, at a height of $\sim(0.07\text{–}0.20)R_s$ (where R_s is the solar radius) and ejected after $\leqslant 30$ min from the beginning of the acceleration, at a certain height reached after this at a transient velocity (bottle or shock front) of ~400–3500 km/s. For the accelerating turbulence in this stage, the less restricted turbulence to accelerate solar particles and to fit observational constraints seems to be the fast MHD mode. In fact, 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., Pérez-Peraza, 1998). This is the kind of turbulence used here for the particle acceleration of the delayed component.

A simplified approach to the problem of turbulent energy supply ignoring non-linear wave–wave interactions

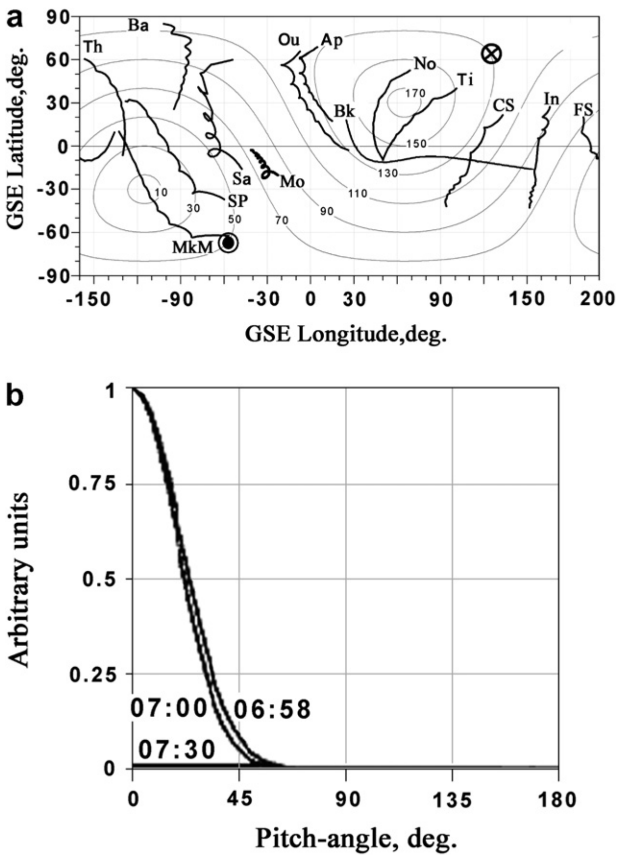

Fig. 2. (a) The derived symmetry axis for the Flux 1 that caused the impulsive giant increase at South Pole and McMurdo stations. The asymptotic viewing cones for vertically incident particles (1–20 GV, the title is at the 20 GV end) for the next NM stations: Th, Thule; Bar, Barentsburg; McM, McMurdo; SP, South Pole; Sa, Sanae; Ma, Mawson; Ou, Oulu; Ap, Apatity; Bak, Baksan; Nor, Norilsk; Ti, Tixie Bay; CS, Cape Schmidt; In, Inuvik; FS, Fort Smith. The IMF direction is indicated by the rounded cross and dot. (b) Dynamics of pitch-angle distribution of the Flux 1.

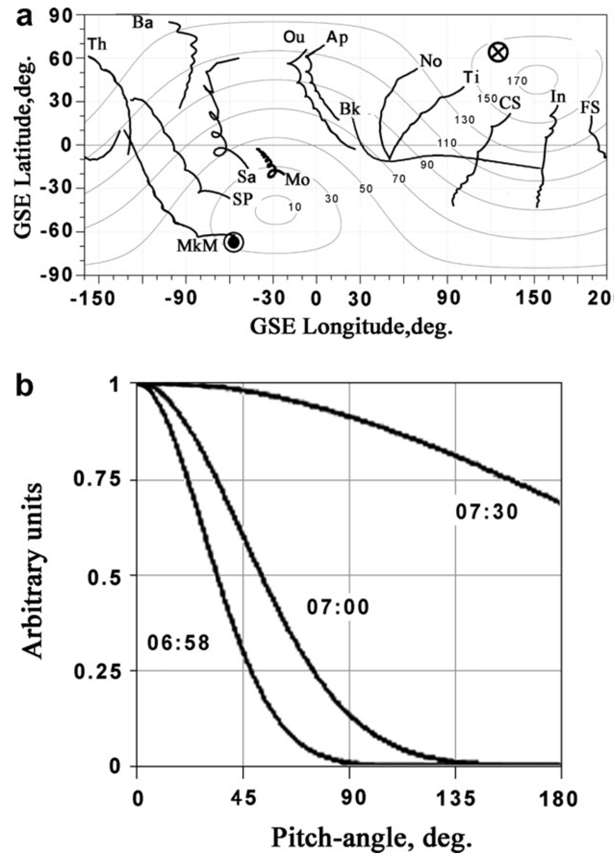

Fig. 3. (a) The derived symmetry axis for the Flux 2 responsible for the increase at the majority NM stations. Designations are the same as in Fig. 2. (b) Dynamics of pitch-angle distribution of the Flux 2.

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 Gallegos-Cruz and Pérez-Peraza (1998) and Gallegos-Cruz et al. (2002), 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, which explains the observational invariability of the spectra slope for delayed component after some time.

Concerning the *source of the prompt component*, the facts that particle ejection of the prompt component is highly abrupt (coronal storage time ≈ 0) and particle flux is highly anisotropic (sharp intensity rise and rapid decay) point toward a source associated with open field lines (rapid particle escape) high in the corona, where particles are efficiently accelerated by a secular (deterministic) process and rapidly collimated through the interplanetary magnetic field lines. Such acceleration may occur during magnetic merging between the expanding magnetic bottle and coronal field lines of opposite polarity (e.g., coronal loops or helmet streamers): 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 by the deterministic electric fields produced in the process of magnetic reconnection.

Schematizations associated with this scenario have been presented in Miroshnichenko et al. (1996) and Miroshnichenko (1997). It should be emphasized that even if the acceleration process of the delayed component begins prior to the production of the prompt component, since the latter one is abruptly generated in an impulsive process in open field line structures, it escapes from the Sun vicinity before the delayed component which is being produced in a magnetic structure which is not openly connected to the IMF lines.

The advantage of this scenario states on the fact that it does not need the assumption of continuous acceleration and/or prolonged trapping of particles to produce delayed particle arrival at the Earth's orbit. However, in order to build a model from such a scenario some of the hypothesis must be substantiated. For a quantitative substantiation of the proposal for the delayed component we have proceeded to evaluate the predicted energy spectra from this kind of stochastic acceleration in order to compare them with observational ones. To do that we use the analytical expressions derived in Gallegos-Cruz and Pérez-Peraza (1995) with the aim of describing solar particle spectra through the entire energy domain (including the trans-relativistic range), which in the particular case of Cherenkov (Landau-damping) acceleration by the fast magnetosonic mode is given in Eq. (3) of the next Section. To substantiate in a quantitative form the proposal for the prompt component, we have proceeded to evaluate the predicted energy spectrum assuming impulsive acceleration in a magnetic neutral current sheet, on basis to the works of Pérez-Peraza et al. (1977, 1978), and then to compare with observational ones.

Results of the applications to specific solar events have been done for a number of large GLEs of the 22–23 solar cycles, in particular, the events of 29 September, 19 and 22 October 1989, 24 May 1990, 14 July 2000, 15 April 2001, 28 October, and 2 November 2003 (e.g., Gallegos-Cruz et al., 2002; Pérez-Peraza et al., 2006; Vashenyuk et al., 2000, 2006). From the comparison of theoretical spectra with observational ones of both components (the delayed component vs. stochastic acceleration and the prompt component vs. deterministic acceleration spectra) the plausible source and acceleration parameters (kind of turbulence, magnetic field strength and configurations, plasma density and temperature) were derived.

Here, we limit our study to the delayed component of the GLE of 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 may be ignored, since we are dealing with relativistic particles (multi-GeV protons measured at ground level).

Up to now, in the derivation of the time-dependent energy spectrum, we have assumed that acceleration efficiency in the case of the GLEs is so high that, in the first approximation, we could ignore energy losses during the acceleration process itself. However, as mentioned above, it should be considered that the first phase acceleration occurs within an expanding plasma. In addition, there is increasing evidence supporting that these kinds of events occur in association with coronal mass ejections (CME) and CME-driven shock waves. So, we analyse below the possibility that adiabatic cooling during the acceleration process in the expanding coronal plasma could have some effect on the energy spectrum. Therefore, we extend our previous analytical study (Pérez-Peraza et al., 2006) by means of the WKBJ method to solve the Fokker–Planck type equation including the term of adiabatic losses.

4. Acceleration model

The formalism of the model is placed within the frame of the very well-known kinetic approach of a momentum–diffusion equation in the phase space for the pitch angle-averaged particle density $f(r,p,t)$, where r, p, and t describe position, momentum, and time, respectively. Assuming spatial homogeneity and a specific turbulence of homogeneous and time-independent type, the transport equation reduces to the following one (e.g., Schlickeiser, 1989):

$$\frac{\partial f(p,t)}{\partial t} = \frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2 D(p)\frac{\partial f(p,t)}{\partial p}\right] \tag{1}$$

By writing the number of the particles N with a velocity v per energy interval at time t in the form of $N(E,t) = 4\pi^2 f(p,t)/v$, where E is the particle kinetic energy, the previous equation can be expressed as a generalized Fokker–Planck type equation. So, by adding the source and escape terms, it can be rewritten as (e.g., Ginzburg and Syrovatskii, 1964; Melrose, 1980):

$$\frac{\partial N(E,t)}{\partial t} = \frac{1}{2}\frac{\partial^2}{\partial E^2}[D(E)N(E,t)] - \frac{\partial}{\partial E}[A(E)N(E,t)] - \frac{N(E,t)}{\tau(E,t)} + Q(E,t) \tag{2}$$

Here, $D(E) = \langle dE^2/dt\rangle = 2v^2 D(p)$ is the diffusive energy change rate and $D(p)$ is the diffusion coefficient in phase space that characterizes the interaction dynamics between particles and the specific type of turbulence. An important factor $A(E) = \langle dE/dt\rangle$ contains all systematic effects of stochastic acceleration and deceleration processes. Also, the source term $Q(E,t)$ and sink term $N(E,t)/\tau$ are added.

Assuming a characteristic escape time $\tau(E,t) = \text{constant}$ (or escape rate $\tau^{-1} = \text{constant}$), Gallegos-Cruz and Pérez-Peraza (1995) derived analytical solutions of this equation (stationary and time-dependent ones) on basis to the WKBJ method. These analytical solutions embrace all energy ranges, unifying previous efforts in partial ranges, the non-relativistic, trans-relativistic and ultra-relativistic. Assuming an injection spectrum $Q(E,t) = q(E)\Theta(t)$ where $\Theta(t)$ is the step function, the general solution is given as:

$$N(E,t) = \frac{D^{1/4}(E)}{(4\pi)^{1/2}}\int_{E_o}^{E}\frac{e^{-R_1(E_o,E')}}{D^{3/4}(E')} \times \left[\frac{N(E',t)}{t^{1/2}}e^{-at-R_2(E_o,E')/t} + \left(\frac{\pi}{4a}\right)^{1/2} q(E')R_3(E_o,E')\right] dE \tag{3}$$

In this derivation, the authors have assumed the systematic acceleration process of Fermi type $\langle dE/dt\rangle = \alpha\beta\varepsilon$, with the acceleration efficiency α (s^{-1}), and diffusive rates of $\langle dE^2/dt\rangle = \alpha\beta^2\varepsilon$, where $\beta = v/c$ is the particle velocity in terms of the light speed and $\varepsilon = E + mc^2$ is the total energy of particles, m is a particle rest mass.

The first term of the right side of Eq. (3) (in the parenthesis) represents the contribution to $N(E,t)$ of an instantaneous injection at time $t = 0$, whereas the second term describes the contribution arising from a continuous injection in energy. The factors $R_1(E_0,E')$, $R_2(E_0,E')$, and $R_3(E_0,E')$ are integral functions, which depend explicitly on the systematic energy gain (and energy loss) rate $\langle dE/dt\rangle$ and on the diffusive rate $\langle dE^2/dt\rangle$ that characterize both the process of stochastic acceleration. Such a solution is exhaustively discussed in terms of Eqs. (15, 26, 41) in Gallegos-Cruz and Pérez-Peraza (1995). For present calculations we will use hereafter Eq. (3) for the particular case of MHD turbulence, with mono-energetic injection, and $D(p) \sim p^2/\beta$ with $\tau = \text{constant}$, corresponding to Eq. (41) of the previous reference.

Recently, Eq. (2) has been solved analytically, using also the WKBJ method, under consideration of an additional term that describes the adiabatic cooling in the systematic energy change rate $A(E)$ (Pérez-Peraza et al., 2006). It was assumed an adiabatic deceleration rate $\langle dE/dt\rangle = -\rho\beta^2\varepsilon$, where $\rho = (2/3)(V_r/R)\ \mathrm{s}^{-1}$ is the adiabatic cooling efficiency, V_r is the velocity expansion and $R(\mathrm{t})$ is the linear extension of the expanding magnetic loop. The obtained analytical formulae can be described as follows. Assuming a mono-energetic continuous injection, $E' \to E_{\mathrm{inj}} = E_0$, Eq. (3) becomes $q(E') = q_0\delta(E' - E_{\mathrm{inj}})$

$$N(E,t) = \frac{kq_0}{2}\left(\frac{3}{4\pi\alpha}\right)^{1/2}\frac{\varepsilon^{3/4}[\varepsilon^2 - m^2c^4]^{-\frac{3\rho}{2\alpha}}}{(\varepsilon^2 - m^2c^4)^{1/8}} \times \left\{[\mathrm{erf}(z_1) - 1]\mathrm{e}^{(3a/\alpha)^{1/2}J} + [\mathrm{erf}(z_2) + 1]\mathrm{e}^{-(3a/\alpha)^{1/2}J}\right\} \quad (4)$$

Where:

$$k = \frac{\left[\varepsilon_0 + \sqrt{\varepsilon_0^2 - m^2c^4}\right]^{3\rho/2\alpha}}{\varepsilon_0^{1/4}(\varepsilon_0^2 - m^2c^4)^{5/8}},$$

$$Z_{1,2} = (at)^{1/2} \pm R_2 t^{-1/2},$$

$$R_2 = (1/2)J(E)\ F(\beta) = \frac{\alpha}{3}(\beta^{-1} + 3\beta - 2\beta^3) - \rho(2 - \beta^2)$$

$$J(E) = (3/\alpha)^{1/2}\left\{\tan^{-1}\beta^{1/2} - \tan^{-1}\beta_0^{1/2} + 0.5\ln\left[\frac{(1+\beta^{1/2})(1-\beta_0^{1/2})}{(1-\beta^{1/2})(1+\beta_0^{1/2})}\right]\right\},$$

$$a(E,\tau) = \tau^{-1} + 0.5[F(\beta_0) + F(\beta)],$$

β_0 is the value of β at the injection energy E_0, ε is the total energy and erf is the error function. In principle, both terms in Eq. (3) contributes to the total spectrum at solar level, however, in practice, the contribution from the initial injection $N_0 \neq 0$ is negligible. For $\rho = 0$, Eq. (4) reduces to Eq. (41) in Gallegos-Cruz and Pérez-Peraza (1995). Spectrum in Eq. (4) tends to a power-law form in the high-energy range as the time elapses toward the steady state situation ($t \to \infty$).

5. Results and discussion

Our calculations for the super-event of 20 January 2005 are based on both Eqs. (3) and (4). The first equation corresponds to the case of pure acceleration, with no adiabatic energy losses ($\rho = 0$), whereas the second one corresponds to a finite value of ρ. In fact, $\rho(\mathrm{t})$ and $\alpha(t)$ are both time functions, however, in this particular case, ρ has been predetermined by assuming a velocity expansion V_r of 3675 km/s (Gopalswamy et al., 2005) and by introducing three linear extensions of the expanding acceleration volume at three different times, $R_1 = 10^{-2}R_s$, $R_2 = 5\times10^{-2}R_s$, and $R_3 = 10^{-1}R_s$, so that $\rho_1 > \rho_2 > \rho_3$. But because ρ_2 and ρ_3 are quite small compared with typical values of $\alpha(t)$, we approximated this parameter to its highest value, that is $\rho_1 \approx \rho = \text{constant}$. Hence, the only real free parameter is $\alpha(t)$.

The best fitting of the experimental data by the spectra given in Eqs. (3) and (4) produces the following acceleration set of parameters for the source spectrum: acceleration efficiency $\alpha = 0.05\ \mathrm{s}^{-1}$, the mean confinement time $\tau = 1.0$ s, the elapsed acceleration time $t = 1.0$ s, the rate of adiabatic cooling $\rho = 0.012\ \mathrm{s}^{-1}$, and the injection energy $E_0 = 1.0$ MeV. Fig. 4 represents this best fitting to the observations for the spectrum of the delayed component of 20 January 2005. In the fitting procedure, the observational data of NM and GOES-11 were used.

The obtained results can be summarized as follows: (1) rather high acceleration efficiency ($\alpha \geqslant 0.05\ \mathrm{s}^{-1}$) 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 from our results whether there was or not a plasma-expanding phenomenon, such as a CME-driven shock wave, simultaneously with the stochastic acceleration stage (3). Nevertheless, the source and acceleration parameters, found for this event from the fitting of theoretical and observational spectra, are within the conventional accepted values.

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

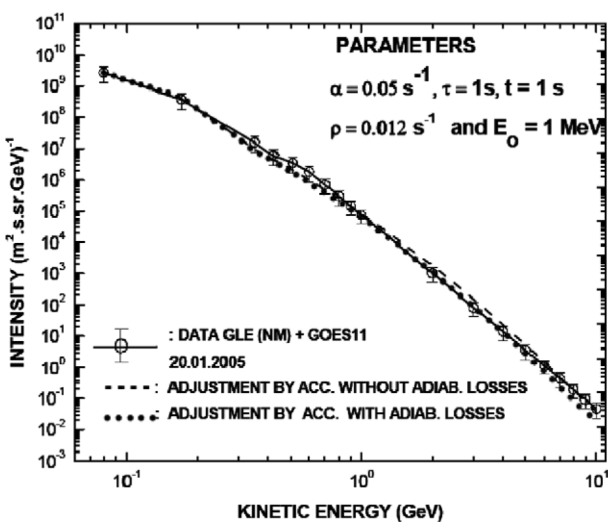

Fig. 4. Adjustment of the experimental energy spectrum of the delayed component of the 20 January 2005 event (open circles) with the theoretical source spectra, considering and ignoring adiabatic losses (slashed and pointed lines, respectively). The obtained parameters are: $\alpha = 0.05\ \mathrm{s}^{-1}$, $\rho = 0.012\ \mathrm{s}^{-1}$, $\tau = 1$ s, $t = 1$ s, and $E_0 = 1$ MeV. Data of ground-based NM at 07:00 UT (with error bars) and GOES-11 observations between 07:00 and 08:00 UT has been fitted by means of least squares.

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 the acceleration efficiency α were of the order of $\sim$0.01–0.001 s^{-1}, as we have found for the GLEs of 14 July 2000 and 15 April 2001 (Vashenyuk et al., 2000), the effect of adiabatic cooling would not be negligible. On the opposite side, in the event of 28 October 2003 the experimental spectrum is very flat (Pérez-Peraza et al., 2006), so that the stochastic acceleration requires of very high acceleration efficiency, perhaps unreal, to reproduce the observational spectrum. It cannot be excluded that the predominant turbulence involved in the acceleration of particles in that event may differ from the predominant one in most of events. It should be noted that in the case of GLE69 the expansion speed of 3675 km/s was higher than in many other events.

In fact, on basis to other observational arguments the Alfvén MHD mode is still a very popular one among solar physicists, because it has a longer mean life time than the other two MHD modes, since they are more resistant to the several dissipation processes that affect them in the turbulent regions of solar flares. However, it should be kept in mind that in the coronal plasma, particle acceleration from resonant interaction with Alfvén waves is only efficient for particles with initial velocities much higher than the local hydromagnetic velocity, and it is required a continuous source of turbulence at a rate $\geqslant 10^3$ erg/cm^3. Such a source has not yet been identified.

6. Conclusions

Here, we have limited our study to the analysis of the delayed component of the GLE of 20 January 2005. We have shown that the adiabatic deceleration is negligible with respect to the acceleration, because the acceleration efficiency for this event turned out to be rather high, while the adiabatic deceleration rate is about 5 times lower than the acceleration rate.

In our modeling of particle evolution in an expanding source a very high speed of expansion (3675 km/s) is assumed. This value was estimated by Gopalswamy et al. (2005) based on the SOHO LASCO data by applying a cone model to the CME. We recognize that existing estimates of the V value are rather controversial, being between 2500 and 3675 km s^{-1} (see, for example, the papers by Gopalswamy et al., 2005; Mewaldt et al., 2005; Tylka, 2006). In fact, a major component of this speed may be actually the outward propagation speed of the CME, which adds to the expansion speed. So, the assumed expansion speed, which is crucial for adiabatic acceleration, is likely overestimated in the model. The authors conclude that adiabatic expansion is negligible, so that a lower value of the expansion speed still strengthens this conclusion. However, if the derived acceleration efficiency were not so high the picture will obviously would change.

Interesting is that the source parameters for fitting the theoretical to the observational spectra turn to be within the order of the low corona values. Similarly, the acceleration parameters range within the order of values inferred by other authors on basis of the secondary radiation of flare emissions. These results seem to support that stochastic acceleration by the fast MHD mode is involved in the generation of the delayed component. Results for the prompt component will be preliminarily presented at the 30 ICRC (Merida, Yucatan, Mexico, 3–11 July 2007).

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References

Bieber, J.W., Clem, J., Evenson, P., Pyle, R., Duldig, M., Humble, J., Ruffolo, D., Rujiwarodom, M., Saiz, A. Largest GLE in half a century: Neutron monitor observations of the January 20, 2005 event. Proc. 29th Int. Cosmic Ray Conf., Pune, India, 1, 237–240, 2005.

Cramp, L.J., Duldig, M.L., Flueckiger, E.O., Humble, J.E., Shea, M.A., Smart, D.F. The October 22, 1989, solar cosmic ray enhancement: an analysis of the anisotropy and spectral characteristics. J. Geophys. Res. 102 (No. A11), 24237–24248, 1997.

Forman, M.A., Ramaty, R., Zweibel, E.G. The acceleration and propagation of solar flare energetic particles, in: Sturrock, P.A. (Ed.), Physics of the Sun. D. Reidel Publ. Co., Dordrecht, pp. 249–289 (Chapter II), 1986.

Gallegos-Cruz, A., Pérez-Peraza, J. Derivation of analytical particle spectra from the solution of the transport equation by the WKBJ method. Astrophys. J. 446, 400–420, 1995.

Gallegos-Cruz, A., Pérez-Peraza, J. On the amount of thermal particles accelerated in the solar corona. Proc. 16th European Cosmic Ray Symp., Alcalá de Henares, Madrid, Spain, p. 141–144, 1998.

Gallegos-Cruz, A., Pérez-Peraza, J., Rodríguez-Frías, M.D., del Peral-Gochicoa, L. Supply of turbulent energy for particle acceleration in astrophysical plasmas. Proc. 6th World Multiconference on Systemics, Cybernetics and Informatics, 17, 426–431, 2002.

Ginzburg, V.L., Syrovatskii, S.I. Origin of Cosmic Rays. Pergamon Press, 1964.

Gopalswamy, N., Hie, H., Yashiro, S., Usoskin, I. Coronal mass elections and Ground Level Enhancements. Proc. 29th Int. Cosmic Ray Conf., Pune, India, 3, 169–172, 2005.

Melrose, D.B. Plasma Astrophysics. Gordon and Breach, New York, 1980.

Mewaldt, R.A., Looper, M.D., Cohen, C.M.S., Mason, G.M., Haggerty, D.K., Desai, M.I., Labrador, A.W., Leske, R.A., Mazur, J.E. Solar-particle energy spectra during the large events of October–November 2003 and January 2005. Proc. 29th Int. Cosmic Ray Conf., Pune India, 1, 111–114, 2005.

Miroshnichenko, L.I. Energetic particles in extended coronal structures: a two-source acceleration scenario. J. Moscow Phys. Soc. 7, 17–30, 1997.

Miroshnichenko, L.I. Solar Cosmic Rays. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 492, 2001.

Miroshnichenko, L.I., Nesterov, V.M., Petrov, V.M., Tibanov, A.P. Prediction of solar cosmic ray spectra on the basis of the recent measurement data. Kosmicheskiye Issledovaniya (Space Research) 12 (6), 892–898 (in Russian), 1974.

Miroshnichenko, L.I., Perez-Peraza, J., Vashenyuk, E.V., Rodríguez-Frías, M.D., del Peral, L., Gallegos-Cruz, A. On the formation of relativistic particle fluxes in the extended coronal structures, in: Ramaty, R., Mandzhavidze, N., Hua, X.-M. (Eds.), High Energy Solar Physics, AIP Conf. Proc. 374. AIP, New York, pp. 140–149, 1996.

Pérez-Peraza, J. Acceleration of solar particles during cycle 22 (Invited Talk). Proc. 16th European Cosmic Ray Symp., Alcalá de Henares, Madrid, España, p. 97–112, 1998.

Perez-Peraza, J., Galvez, M., Lara, A. Energy spectrum of flare particles from an impulsive acceleration process. Proc. 15th Int. Cosmic Ray Conf., Plovdiv, Bulgaria, 5, 23–28, 1977.

Pérez-Peraza, J., Gálvez, M., Lara, R. The primary spectrum of suprathermal particles. Adv. Space Res. 18, 365–368, 1978.

Pérez-Peraza, J., Gallegos-Cruz, A., Vashenyuk, E.V., Balabin, Yu.V., Miroshnichenko, L.I. Relativistic proton production at the Sun in the October 28th, 2003 solar event. Adv. Space Res. 38 (3), 418–424, 2006.

Sakurai, K. Physics of Solar Cosmic Rays. Tokyo University Press, Tokyo, 1974.

Schlickeiser, R. Cosmic-ray transport and acceleration: I. Derivation of the kinetic equation and application to cosmic rays in static cold media. Astrophys. J. 336, 243–263, 1989.

Shea, M.A., Smart, D.F. Possible evidence for a rigidity-dependent release of relativistic protons from the solar corona. Space Sci. Rev. 32, 251–271, 1982.

Tylka, A.J. The historic solar event of January 20, 2005: A challenge for current theories on the origin of solar energetic particles? Prepared for the 2006 SHINE Workshop, 31 July–4 August 2006, Zermatt, Utah, http://creme96.nrl.navy.mil/20Jan05/.

Vashenyuk, E.V., Miroshnichenko, L.I., Gvozdevsky, B.B. Proton energy spectrum and source parameters of the September 29, 1989 event. Nuovo Cimento 23, 285–291, 2000.

Vashenyuk, E.V., Balabin, Yu,V, Gvozdevsky, B.B., Karpov, S.N., Yanke, V.G., Eroshenko, E.A., Belov, A.V., Gushchina, R.T. Relativistic solar cosmic rays in January 20, 2005 event on the ground based observations. Proc. 29th Int. Cosmic Ray Conf., Pune, India, 1, 209–212, 2005a.

Vashenyuk, E.V., Balabin, Yu.V., Bazilevskaya, G.A., Makhmutov, V.S., Stozhkov, Yu.I., Svirzhevsky, N.S. Solar particle event of 20 January, 2005 on stratosphere and ground level observations. Proc. 29th Int. Cosmic Ray Conf., Pune, India, 1, 213–216, 2005b.

Vashenyuk, E.V., Balabin, Yu.V., Perez-Peraza, J., Gallegos-Cruz, A., Miroshnichenko, L.I. Some features of the sources of relativistic particles at the Sun in the solar cycles 21–23. Adv. Space Res. 38 (3), 411–417, 2006.