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Relativistic proton production at the sun in the October 28th, 2003 solar event

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Abstract

In order to infer about the origin of solar relativistic particles (SRP) from the particle event of October 28th, 2003, we proceed to do a confrontation of the experimental energy spectra with the theoretical spectra derived from a transport equation for stochastic acceleration. On basis to a two-source model of particle generation, one of which is associated with an expanding magnetic loop, we solve the transport equation including adiabatic losses simultaneously with the stochastic acceleration process. The confrontation shows that there are two different populations during this event, one of which, the so-called "delayed component" may be correctly described by stochastic acceleration, but not the so-called "prompt component". We found that the required acceleration efficiencies turn to be very high, so that for this particular event, adiabatic cooling is practically negligible as far as the energy spectrum is concerned. Qualitative inferences point toward a dominated Alfven accelerating turbulence. Our results provide a new support to the existence of two relativistic particle populations in some solar relativistic particle events.
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Keywords: Relativistic solar particles; Stochastic acceleration; Energy spectra

1. Introduction

Some years ago we had succeeded to derive an analytical expression for the whole time-dependent energy spectrum of stochastically accelerated particles, which uses to exist in partial energy ranges: non-relativistic, transrelativistic (numerically) and ultrarelativistic domains. That was done by solving the momentum-diffusion equation by means of the WKBJ method (Gallegos-Cruz and Pérez-Peraza, 1995). When applied to the production of solar particles, we did it for the case of solar relativistic particle (SRP) events, that is, the so-called ground level events (GLE), specifically those which present two relativistic particle populations. In a series of works (Vashenyuk et al., 1994, 1997, 2002), we derived the plausible source and acceleration parameters for events of the 22 and 23 solar cycles. That was done from the confrontation of theoretical with observational spectra for both components: the DC vs. stochastic acceleration and the PC vs. deterministic acceleration spectra. Results were extensively discussed by Pérez-Peraza, 1998 and Miroshnichenko, 2001.

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The scenario for such a kind of events is developed in terms of two different sources of particle acceleration: a prompt component (PC), which acceleration is carried our by a deterministic process in a magnetic neutral current sheet (MNCS) high in the corona, in a region of open field lines, and a delayed component (DC) where the bulk of particles are stochastically accelerated during the impulsive phase in the flare body, within an expanding closed magnetic structure in the low corona. Here, we limit our study to the DC of the October 28th, 2003 GLE, which experimental data is shown in Figs. 1–3.

Though the event took place in the S-E of the sun, and in principle effects of azimuthal propagation could alter the energy spectrum, we ignore them in first instance, since we are dealing with relativistic particles (Multi-GeV protons measured at ground level). Up to now we have assumed in the derivation of the time-dependent spectrum, that acceleration efficiency in these cases of SRP events is so efficient, that we could in first approximation, ignore energy losses during the acceleration process itself. However, taking into account that this first phase acceleration occurs within an expanding plasma, and there is increasing evidence supporting that these kinds of events occur in association with Coronal

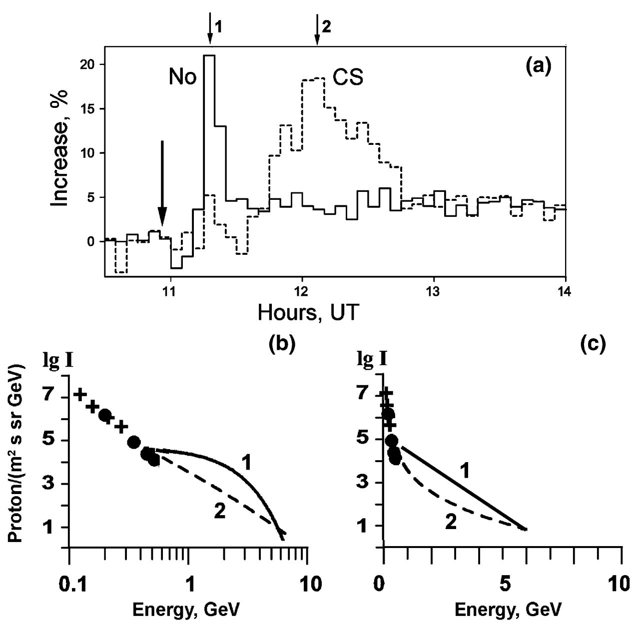

Fig. 1. Prompt and delayed components of relativistic solar protons (RSP) in the GLE 28.10.2003. (a) intensity profiles at the NM stations: Norilsk (No) and Cape Schmidt (CS). The prompt impulse-like increase seen by Norilsk and Cape Shmidt belong to the prompt component (PC) of RSP. The wide delayed maximum at the Cape Shmidt profile is the delayed component (DC). Numbered arrows 1 and 2 mark the moments of time when the spectra of PC and DC of RSP shown below were derived. (b) Spectra of PC (1) and DC (2) in double logarithmic and semi-logarithmic (c) scales. Note an exponential form of the prompt component spectrum (1) and the power law form of the delayed component spectrum (2).

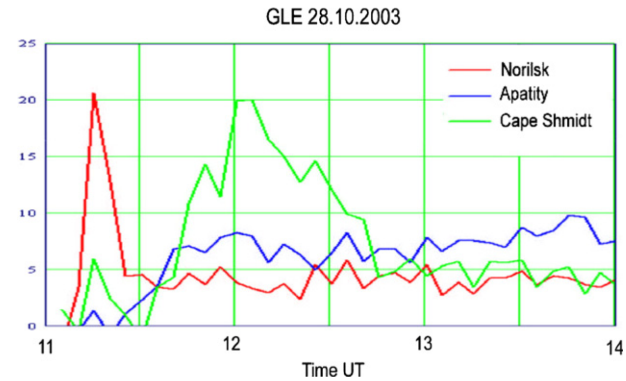

Fig. 2. Time profile of the GLE of October 28, 2003 as seen by three Neutron Monitor Stations: Norilsk Station registered a very clear sharp peak by 11:20 UT and Cape Schmidt Station registered also a very clear peak by 12:10.

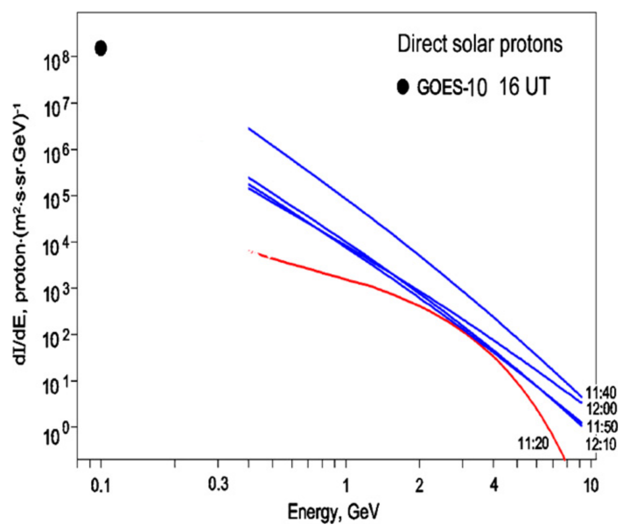

Fig. 3. Energy Spectra of the Multi-GeV Solar Particle Event of October 28, 2003, at different times. The black point at 100 MeV corresponds to data from the satellite GOES-10 at 16:00 UT.

Mass Ejections-driven shock waves, we analyze here 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 by means of the WKBJ method (Gallegos-Cruz and Pérez-Peraza, 1995) to solve the Fokker–Planck type equation including the term of adiabatic looses.

2. The 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 can be reduced 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 $N(E, t) = 4\pi^2 f(p, t)/v$ the previous equation can be expressed as a generalized Fokker–Planck type equation, so that by adding a source and escape terms it can be rewritten as (e.g., Ginzburg and Sirovatskii, 1964; Melrose, 1980):

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

where $D(E) = \langle dE^2/dt\rangle = 2v^2 D(p)$, is the diffusive energy change rate, $D(p)$ is the diffusion coefficient that characterizes the interaction dynamics between particles and the specific type of turbulence, $A(E) = \langle dE/dt\rangle \pm$ additional systematic energy processes. Assuming a constant escape rate, Gallegos-Cruz and Pérez-Peraza (1995) derived an approximated solution of this equation on basis to the WKBJ method:

$$N(E,t) = \frac{D^{1/4}(E)}{(4\pi)^{1/2}}\int_{E_0}^{E}\frac{e^{-R_1(E_0,E')}}{D^{3/4}(E')}\left[\frac{N(E',t)}{t^{1/2}}e^{-at-R_2(E_0,E')/t} + \left(\frac{\pi}{4a}\right)^{1/2} q(E')R_3(E_0,E')\right]dE'\ldots[3] \tag{3}$$

where it has been assumed a systematic acceleration and diffusive rates of the Fermi type $\langle dE/dt\rangle = \alpha\beta\varepsilon$ and $\langle dE^2/dt\rangle = \alpha\beta^2\varepsilon$, where α (s^{-1}) is the acceleration efficiency, $\beta = v/c$ is the particle velocity in terms of the light speed, ε the total energy of particles and E is the particle kinetic energy. The considered injection spectrum is given by $q(E) = q_0\delta(E - E')$, where q_0 is the initial amount of particles at time $t = 0$ with energy E_0, such that $E_0 \leqslant E' \leqslant E$. The first term of the right side of Eq. (3) represents the contribution to $N(E, t)$ of an instantaneous injection at time $t = 0$, whereas the second term represents the contribution arising from a continuous injection in energy. $R_1(E_0, E')$, $R_2(E_0, E')$ 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 and 41) in Gallegos-Cruz and Pérez-Peraza (1995).

Here, we solve Eq. (2) by the same method, under the consideration of an additional term, that of the adiabatic cooling in the systematic energy change rate. Therefore, we assume an adiabatic deceleration rate $\langle dE/dt\rangle = -\rho\beta^2\varepsilon$, where $\rho = (2/3)(Vr/R)$ (s^{-1}) is the adiabatic cooling efficiency, Vr is the velocity expansion and $R(t)$ is the linear extension of the expanding magnetic loop. Again by the WKBJ method we obtain the following analytical solution:

$$N(E,t) = kq_0 f(E)\{[\mathrm{erf}(z_1) - 1]e^{a^{1/2}J(E)} + [\mathrm{erf}(z_2) + 1]e^{-a^{1/2}J(E)}\}, \tag{4}$$

where $f(E)$, $a(E, \tau)$ and $J(E)$ are analytic functions of the energy described in (Gallegos-Cruz and Pérez-Peraza, 1995), k is a constant and erf represents the error function.

$$f(\varepsilon) = (\varepsilon^2 - m^2c^4)^{3/8}\varepsilon^{-1/4},$$
$$a(E,\tau) = \tau^{-1} + 0.5[F(\beta_0) + F(\beta)],$$
$$F(\beta) = \frac{\alpha}{3}(\beta^{-1} + 3\beta - 2\beta^3) - \rho(2 - \beta^2),$$

$Z_{1,2}$ and $J(E)$ have the same meaning that in (Gallegos-Cruz and Pérez-Peraza, 1995). That is $Z_{1,2} = (at)^{1/2} \pm R_2 t^{-1/2}$ with $R_2 = \frac{1}{2}J(E)$ and

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

β_0 is the value of β at the injection energy E_0.

Spectra (3) and (4) tend to a power law in the high energy range as the time elapses toward the steady state situation.

3. Results and analysis

Our calculations are based on both Eqs. (3) and (4). The first equation corresponds to the case of pure acceleration with no energy losses ($\rho = 0$), whereas the second one corresponds to a finite value of ρ. In fact $\rho(t)$ and $\alpha(t)$ are both time functions, however ρ has been predetermined by assuming a velocity expansion $Vr = 1000$ km/s, and three linear extensions of the expanding acceleration volume at three different times, $R_1 = 10^{-2}$ Rs, $R_2 = 5 \times 10^{-2}$ Rs and $R_3 = 10^{-1}$ Rs (where Rs = solar radius), so that $\rho_1 > \rho_2 > \rho_3$, but because ρ_2 and ρ_3, are quite small compared with typical values of α, we approximated this parameter to its highest value, that is $\rho_1 \approx \rho = 4.4 \times 10^{-2}\ s^{-1}$ = cte. Hence, the only real free parameter is $\alpha(t)$. The obtained results can be summarized as follows:

- Very high acceleration efficiencies ($\alpha > 0.6$) are needed in order to obtain a good fitting of the experimental data (Table 1).
- For such high efficiency values, the term of adiabatic deceleration has practically no contribution. That avoids us to infer whether there was or not a plasma

Table 1
Acceleration parameters: the acceleration efficiency α, the mean confinement time τ, the elapsed acceleration time t and the injection energy E_0 used in Figs. 4–7

α (s^{-1})	τ (s)	t (s)	E_0 (MeV)	Figure
4.5	0.1	1.0	10	4
0.9	1.0	4.0	1	5
0.7	1.0	10	1	6
0.65	0.9	20	1	7

expanding phenomenon, such as a CME-driven shock wave, simultaneously with the stochastic acceleration stage.

- Fittings can be obtained with very good precision, with the exception of the spectrum of the first time experimental register (11:20 U.T.), in which case extremely high values of the acceleration efficiency are needed to approach the data curve (Fig. 4).
- As the time elapses the required efficiency values become gradually lower (Figs. 5–7).

Let analyze these results: we find that the so-called prompt component cannot be explained by stochastic acceleration, whereas the delayed component can be in a straight way explained by spectra from stochastic acceleration. This result effectively points toward the

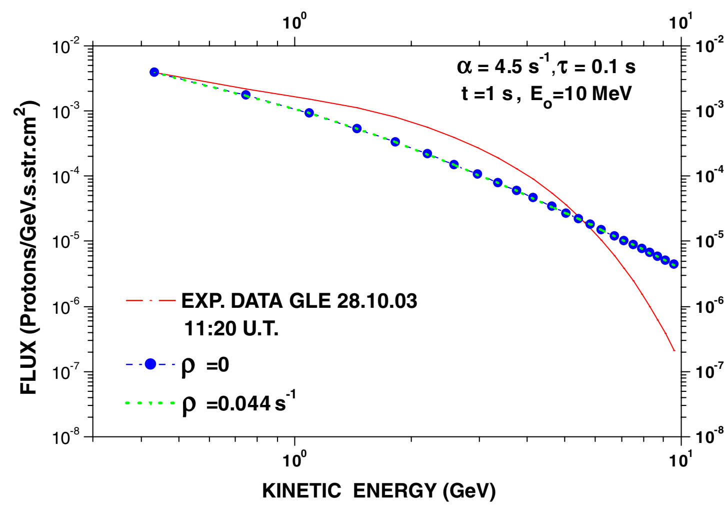

Fig. 4. Fitting of the experimental energy spectrum at 11:20 UT with Eq. (4), considering a realistic value of the adiabatic cooling ($\rho = 0.044\ s^{-1}$) and ignoring it ($\rho = 0$). The acceleration parameters that produce the closest adjustment are: a mean confinement time $\tau = 0.1$ s, an acceleration time $t = 1$ s, and extremely high values for the acceleration efficiency $\alpha = 4.5\ s^{-1}$ and injection energy of 10 MeV.

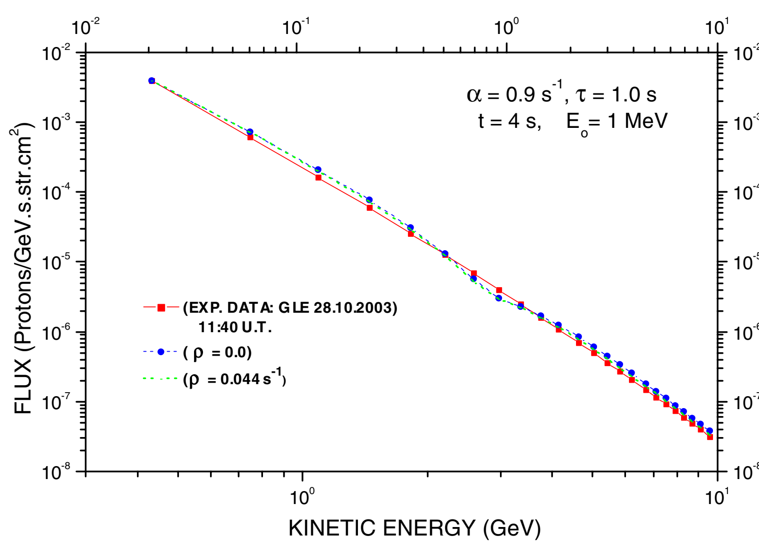

Fig. 5. Fitting of the experimental energy spectrum at 11:40 UT with Eq. (4), considering a realistic value of the adiabatic cooling ($\rho = 0.044\ s^{-1}$) and ignoring it ($\rho = 0$). A good fitting is obtained with a mean confinement time $\tau = 1$ s, acceleration time $t = 4$ s, acceleration efficiency $\alpha = 0.9\ s^{-1}$ and injection energy of 1 MeV.

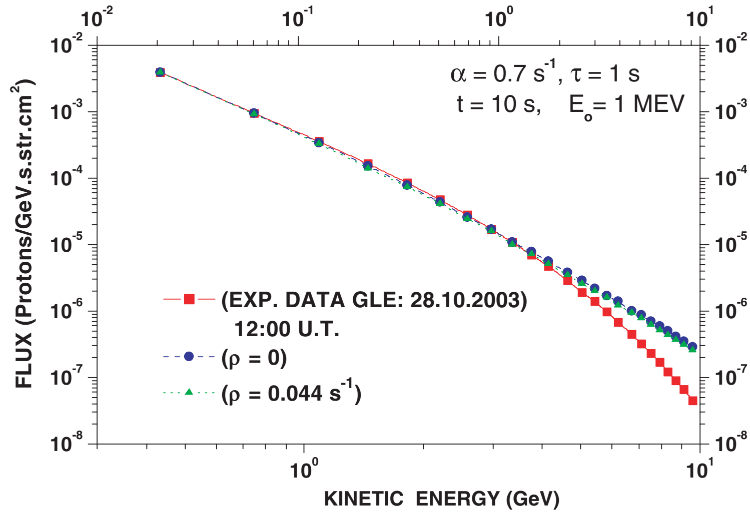

Fig. 6. Fitting of the experimental energy spectrum at 12:00 UT with Eq. (4), considering a realistic value of the adiabatic cooling ($\rho = 0.044\ s^{-1}$) and ignoring it ($\rho = 0$). The best fitting is obtained with a mean confinement time $\tau = 1$ s, acceleration time $t = 10$ s, acceleration efficiency $\alpha = 0.7\ s^{-1}$ and injection energy of 1 MeV.

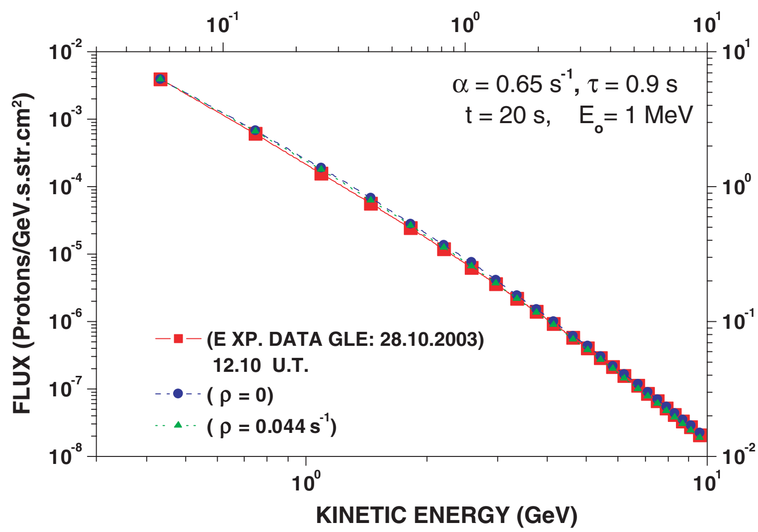

Fig. 7. Fitting of the experimental energy spectrum at 12:10 UT with Eq. (4), considering a realistic value of the adiabatic cooling ($\rho = 0.044\ s^{-1}$) and ignoring it ($\rho = 0$). A good fitting is obtained with a mean confinement time $\tau = 1$ s, acceleration time $t = 20$ s, acceleration efficiency $\alpha = 0.65\ s^{-1}$ and injection energy of 1 MeV.

confirmation of two components of different origin. Within the frame of the proposed scenario in the mentioned references (e.g., Miroshnichenko, 2001), the delayed component is generated into a closed expanding magnetic structure, that in the course of such an expansion get in touch with other loops, one of which may be of opposite polarity, creating a Magnetic Neutral Current Sheet where local particles in its diffusion region, are impulsively accelerated by the deterministic electric fields produced in the process of magnetic reconnection (Miroshnichenko et al., 1996). Such deterministically accelerated particles are seen at earth around 11:20 UT as a prompt component. The enclosed component (undergoing stochastic acceleration by the generated turbulence in the expanding plasma) is susceptible of loosing energy by adiabatic cooling while they are being accelerated: assuming the magnetic loop associated to the flare begins to expand around 11:02 UT (according to the type II radio onset of the 4 B/X17.2/S16 E08 flare), and taking into account that relativistic particle last about 8 min. to reach the earth, the first bunch measured at 11:40 UT must have been generated before ~11:32, when the acceleration efficiency $\alpha(t)$ has reached a value enough high to overcome the energy loss barrier, say $\alpha_1 \approx 0.9\ s^{-1}$ and the observed particles spend 4 s under this acceleration efficiency. Later, after 10 s the stochastic process efficiency decreases to a value $\alpha_2 \approx 0.7\ s^{-1}$ such that particles measured at 12.00 UT have been accelerated under this efficiency regime, finally after 20 s of acceleration, the efficiency decreases to $\alpha_3 \approx 0.65\ s^{-1}$ where the steady state (α = cte.) is practically being reached, the magnetic structure is open and turbulence is dissipated (particles under this regimen are measured at about 12:10). Under the present scenario, the expansion begins around 11 UT; the stroke to the collateral loop occurs at ~11:10 (particles of this prompt component are measured on earth at 11:20 UT), that implies that the "population in the expansion bottle" has been about half an hour undergoing adiabatic cooling, competing with stochastic acceleration up to the moment that efficiency reach the value α_1 to overcome the loss barriers and begin to escape with an average escape time of about 1 s.

It must be emphasized that we could not predict at the 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 values of the acceleration efficiency are practically the same with both Eqs. (3) and (4), even though the spectra are slightly distinguishable. It is clear that if the derived values of α were of the order of ~0.01–0.001 s^{-1} as we have found for the 14.07.2000 and 15.04.2001 SPE, the effect of adiabatic cooling would not be negligible. But for this particular event of 28.10.2003 the experimental spectra are very flat, so that the stochastic acceleration requires of very high acceleration efficiency to reproduce them.

Concerning how realistic are these efficiencies between 0.65 and 0.9 s^{-1}, we would like to emphasize again that these high values for this particular SPE have been obtained from the confrontation of the theoretical spectra with the observational ones. These acceleration efficiencies (α) are defined by the best fits. As far as theoretical work is concerned (Gallegos-Cruz and Pérez-Peraza, 1995 and reference therein) typical values are not higher than 0.3 s^{-1}, however, when confrontation is made with experimental spectra we found here, that at least for this very energetic event, the efficiencies may be twice and even three times the predicted ones by purely theoretical work. On the other hand, we should remark that in previous comparisons with experimental data (the 14.07.2000 and 15.04.2001 events), we have obtained lower values of (α). The reason is that the experimental spectra of this particular event of the 28th October, 2003 is flatter than the previous analyzed events. The predominant turbulence involved in the acceleration of particles in this event may differ from the predominant one in other events.

At this regard, we would like to remind that the relative efficiency for turbulent acceleration among different wave modes, that presumably could develop and subsist for some time in the turbulent flare plasma, has been summarized in Pérez-Peraza, 1998 (Tables 1 and 2). 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 acceleration process in the non-relativistic particle domain but not for relativistic solar particles (Gallegos-Cruz et al., 1995). Besides, it is well known that due to mass motions, magnetic reconnection and instabilities of macroscopic magnetized systems in flare plasma, the presence of MHD turbulence seems highly probable (Perez-Peraza et al., 1997). Slow magnetosonic mode of MHD turbulence may be an interesting option to accelerate particles from the thermal background at chromospheric levels (Gallegos-Cruz et al., 1993), but in the coronal flare plasma requires of a continuous source of turbulence at a rate $\geqslant 10^3$ erg/cm^3. The same requirement of turbulent energy density is needed for resonant interaction particle-Alfven 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 (Gallegos-Cruz and Perez-Peraza, 1998; 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 (Gallegos-Cruz and Pérez-Peraza, 1995; Gallegos-Cruz et al., 2002), which explains the invariability of DC spectra slope after some time. However, the number of accelerated protons is many orders of magnitude smaller than the observational intensity. To fit the observed amount of accelerated particles,it must be assumed an injection to the process with a supra-alfvenic energy E_0, though a non-linear analysis including cascade effects (Lenters and Miller, 1998) leads to an increase of the acceleration efficiency, allowing particles to be accelerated from the thermal background. A relevant discussion also was done in Gallegos-Cruz et al., 1993 and in Gallegos-Cruz and Pérez-Peraza, 1995 (Section 3).

Now, coming back to our particular SRP event, we should like to point out that 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. For the acceleration process the Alfven mode requires higher energy density than the fast mode, and due that energy density is proportional to the acceleration efficiency, consequently higher values of (α) do operates with these kind of waves. Since we find here from the confrontation of experimental and theoretical spectra that the efficiencies are higher than with our previous analysis of other solar events, we infer that the Alfven mode may have prevailed during this event.

4. Conclusions

The analysis carried out with the application of the stochastic acceleration model to the GLE of October 28th, 2003 supports the evidence that there are two different sources of relativistic particles in this SPE. One of gradual nature (the DC), which spectra is quite well reproduced by stochastic acceleration, as is shown through Figs. 3–5, at 11:40, 12:00 and 12:10 UT respectively, and another of impulsive-deterministic nature (the PC) which spectrum cannot be reproduced by stochastic acceleration, as is shown in Fig. 4 at 11:20 UT (this may eventually be reproduced, as was done by Miroshnichenko et al. (1996) in the case of the September 29 and October 22, 1989 events, by means of acceleration in a MNCS according to the model proposed in Pérez-Peraza et al., 1978). Considering the discussion given in Gallegos-Cruz and Pérez-Peraza (1995) regarding acceleration efficiencies from the fast MHD turbulence mode and the high values of ($\alpha = 0.65$ and $0.9\ s^{-1}$) determined in this work, we are lead to think that this event was dominated by the Alfven MHD mode. However, it should be emphasized that this is a qualitative inference and further quantitative analysis must be done on the turbulence diffusion coefficients in order to elucidate whether such high values of α are consistent with Alfven waves or the fast MHD mode.

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