# HIGH ENERGY SOLAR PHYSICS

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# On the Formation of Relativistic Particle Fluxes in Extended Coronal Structures

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We analyze neutron monitor data of solar cosmic rays in order to obtain information about their sources. We use three methods for these data analysis. As result, we obtain a set of evidences for two separate solar cosmic rays sources that we call as prompt and delayed components. We attempt here to substantiate a two sources scenario for the generation of both components. For the prompt component source, we suggest regular acceleration in a neutral current sheet. For the delayed one, we propose acceleration by magnetosonic wave turbulence.

## INTRODUCTION

The first mention of the possible existence of two separate components for relativistic solar cosmic rays was raised in (1). Independently, *Ramaty et al.* in (2), investigating the relevant amount of all solar cosmic rays generated by the June 3, 1982 flare, also approached towards a two components scenario. The first population is accelerated during the flare flash phase and the particles are trapped, low in the solar atmosphere, into closed magnetic structures. The second component is generated high in the solar corona, at a second acceleration phase, by a coronal shock wave belonging to the same flare.

Certain evidences of two relativistic protons ejections were found (3) for the September 29, 1989 ground level event (GLE). Some peculiarities of this GLE may be explained by a two separate acceleration sources model (4).

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# OBSERVATIONAL DATA OF RELATIVISTIC SOLAR COSMIC RAYS

The study of solar cosmic rays at relativistic energies ($E > 500$ $MeV$ for protons) provides an opportunity to obtain new information about acceleration processes in solar particle sources. In particular, it is usefull to clarify some features of the solar accelerators and estimate a number of important parameters of solar cosmic ray sources (upper energy limits of the acceleration mechanisms, the particle ejection time from the corona, etc.).

For the 54 GLEs registered since 1942, fourteen of them were recorded in the current 22nd solar cycle. Some of these GLEs display a set of peculiarities which seem to need interpretation under a new conceptual base.

The relativistic solar cosmic rays are detected at ground level by several neutron monitor stations around the world. We use three methods for the analysis and comparison:

1. Semiquantitative physical characteristics comparison of relativistic solar particles obtained by different neutron monitor during the same event.

2. $vT_m$ technique, where $v$ is the particle velocity and $T_m$ is the maximum intensity time at 1 AU.

3. $T_{1/2}$ is the intensity-time profile half width.

## Physical Characteristics of Relativistic Solar Particles

It is well known that the shape of the intensity-time profiles contains important information about the solar cosmic rays ejection time and their transport through the corona and the interplanetary space.

In several events, some neutron monitor stations, magnetically well connected with the source, are able to detect both, sharp and scattered peaks. In Fig. 1 we can observe that Apatity and Oulu neutron monitor stations located at the north hemisphere did not detect two peaks for the October 22, 1989 event, while the South Pole station did it. The reason is that South Pole station is located in the south hemisphere well connected with the flare site 27S32W.

The sharp peak particles show an anisotropic behaviour, while the smooth peak particles are fully isotropic distributed. This suggest us different sources for both components.

Fig.2. shows, for a given neutron monitor station, the dependence of the solar cosmic ray flux on the angular distance from the anisotropy axis ($\theta = 0°$) (boxes A and B in the upper left diagram) during the November 18, 1968 GLE; at the right there are the time profiles corresponding to the anisotropic component of box A and the scattered component in box B (5). The situation shown at Fig. 2. is typical for many GLEs, and in all these cases, one cannot

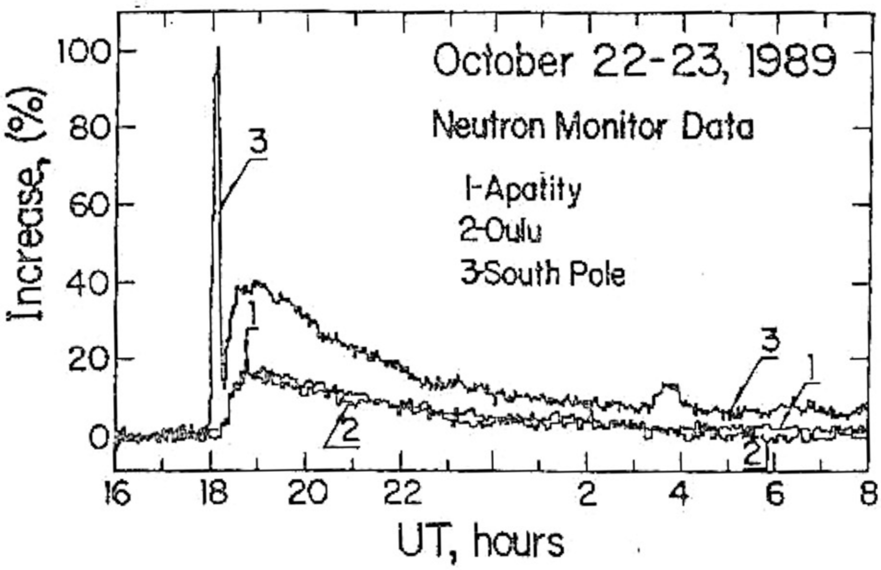


FIG. 1. Intensity-time profiles of the October 22, 1989 GLE obtained by the neutron monitors at three different stations: 1-Apatity, 2-Oulu and 3-South Pole.

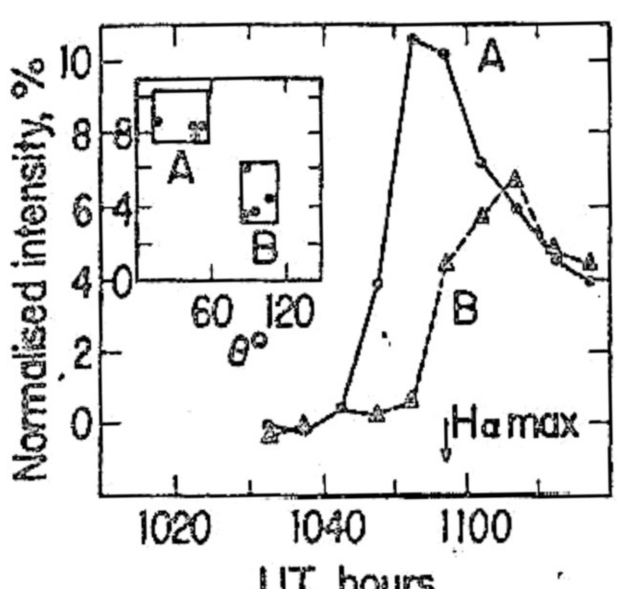


FIG. 2. Isotropic (A) and anisotropic (B) components of solar cosmic rays in the November 18, 1968 GRL. The angle $\theta = 0°$ corresponds to the average IMF direction [*Duggal et al.*, 1971].

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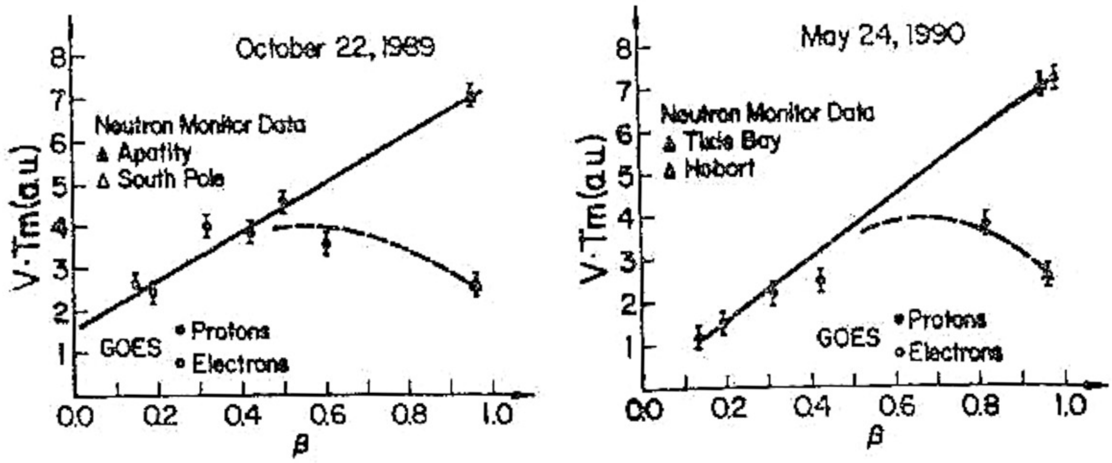


FIG. 3. $vT_m$-analysis for two GLEs observed in the 22nd solar cycle: October 22, 1989 and May 24, 1990.

always find any suitable shock or any other ideal reflecting boundary behind the Earth's orbit able to produce the scattered component, as it was often assumed (6). So, the scattered component is isotropically ejected from the corona and cannot be attributed to an isotropization during the transport in the interplanetary space.

The rigidity spectra of those two populations show different slopes in a single event (7). The particles of the sharp peaks show flatter spectra than those of the scattered peaks.(19)

## $vT_m$ Technique

This method was developed by *Reinhard and Wibberenz*, (8) and followed by *Van Hollebeke, et al.*, (9) and *Ma Sung et al.*, (10), on basis to the following relations:

$$vT_n = A_n + B_n v \quad (1)$$

$$vT_m = A_m + B_m v \quad (2)$$

$T_n$ : is the onset time;

$T_m$ : is the maximum intensity time;

$A_n$ : is the path of onset particles through IMF;

$A_m$ : is the path of the main bulk particles through IMF;

$B_n$ : is the time spent by onset particles in the corona;

$B_m$ : is the time spent by the main bulk in the corona;

Fig. 3 demonstrate the results of $vT_m$-analysis for two GLEs observed in the 22nd solar cycle, namely, October 22, 1989 and May 24, 1990, respectively. It is seen, in particular, that the October 22, 1989 event had both components,

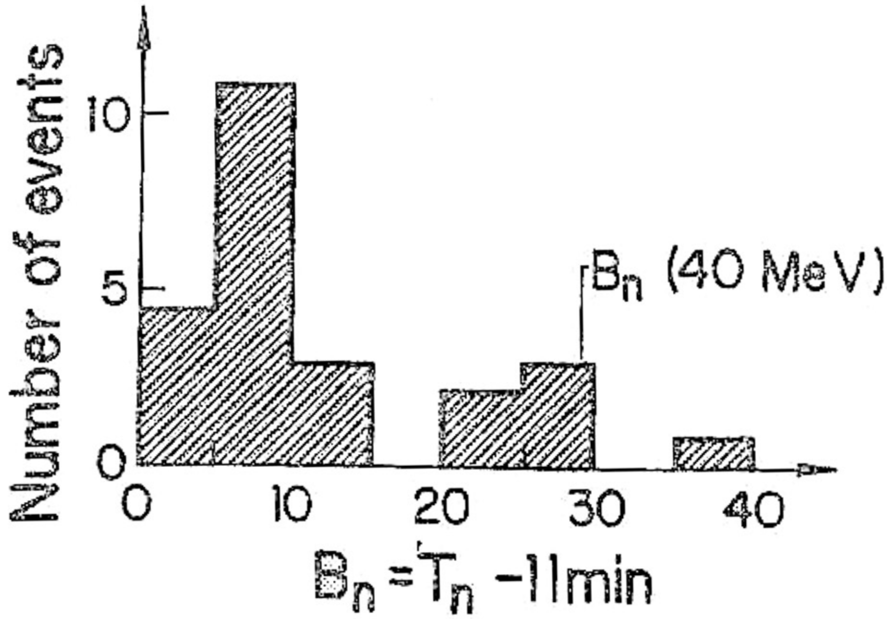


FIG. 4. Distribution of solar proton events number versus $B_n$ parameter.

the prompt component being registered by NMs (above 500 MeV) as well as by proton detector on board the GOES satellite (above 200 MeV), meanwhile the delayed was registered in the entire range of SCR energies. The same is follows for the May 24, 1990 event, the delayed component being present also in relativistic electron population.

Conclusions of this analysis were that, if we take 11 *min* as the time spent by the first particles in the interplanetary space (11), we can obtain the spent time in the corona, $B_n$, from equation (1). As shown in Fig. 4 this parameter takes two different values for the time spent by energetic particles in the solar corona by the two different solar flare particles populations. The particle population of the sharp peak gives values for the $B_n$ parameter between $0 - 15$ *min* and the particle population of the scattered peak gives $B_n$ about 30 *min* in coincidence with the 29 *min* satellite data for the 40 *MeV* energy range (12). We also obtain two componets from the total path through the IMF of the main bulk particles ($vT_m$) analysis using equation (2). The particles of the sharp peak, have shorter paths ($vT_m \sim 2 - 3$ AU) than the particles of the scattered peak (with $vT_m \sim 7$ AU). This difference was also detected for protons by the GOES satellite in the October 22, 1989 GLE (13).

## The Intensity-Time Profile Width

To derive essentially new information from GLE data it was suggested by *Vashenyuk et al.* (14) to use a specific parameter $T_{1/2}$. This parameter seems to be a measure of the time spent by the main bulk particles in the corona. The $T_{1/2}$ versus heliolongitude plot of the related flares for 42 GLEs points out that the dots concentrate in two zones, corresponding to two different heliolongitude distributions. The sharp component events have $T_{1/2} < 1$ *hr* and were produced at heliolongitudes between 20-130 W in the box region of

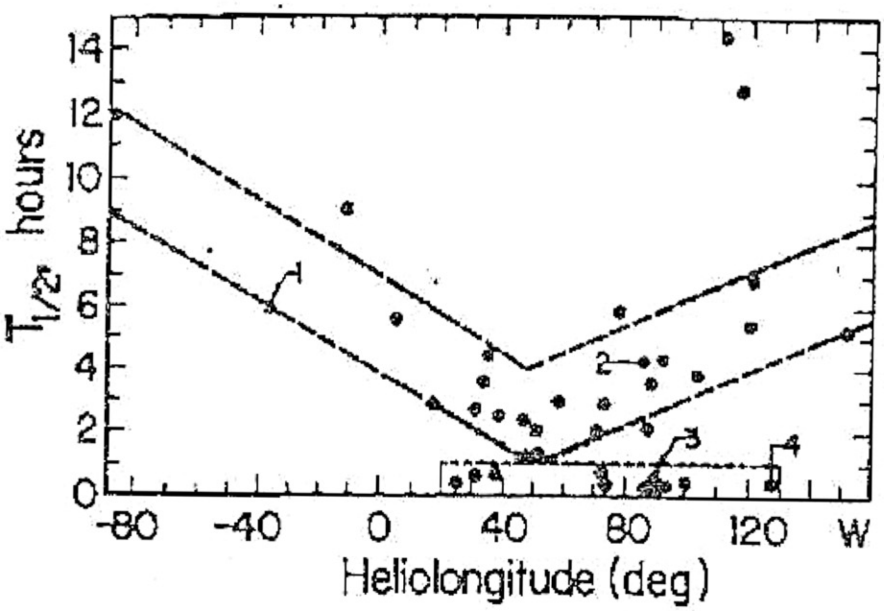


FIG. 5. Heliolongitude distribution of $T_{1/2}$, the intensity-time profiles half-width of GLEs.

Fig. 5. The scattered component events lie on a V-shape band with minimum at 50W, near the well connected line of IMF to the Earth and have similar behaviour to the same distribution for solar protons in the energy range 20-80 MeV (9). All of them, have $T_{1/2} > 1\ h$ and they were produced at heliolongitudes between 90 E - 150 W.

## INTERPRETATION

Observational results considered above provide evidences of two components in relativistic solar protons events, that are apparently independent. According with previous investigations, we can state with more confidence that we deal with two components: a prompt component, which produces the sharp and anisotropic peak; and a delayed one, which produces the scattered and isotropic peak. However there are some stations that can only detect one of the components. The anisotropy characterizes the sources for both components. So, the prompt component must have an anisotropic source located in a region with open field lines (probably high in the corona), while the delayed component is associated with the magnetic bottle destroyed through plasma instabilities and reconnection of the disordered magnetic field lines.

The acceleration of the delayed component is carried out by the dissipation of local turbulence to a select number of particles able to undergo resonant interaction with the turbulence wave modes. When expanding, the flare-generated magnetic bottle gets in touch with the neighbouring magnetic arcade at heights $\sim 0.5 - 1\ R_{\odot}$ where a neutral current sheet may be formed due to magnetic reconnection between lines of opposite polarity (Fig. 6). Local particles in the non-adiabatic region of the neutral current sheet may be accelerated by the intense impulsive electric fields produced by the magnetic merging process. According to *Pérez-Peraza et al.* (15) the energy spectrum of the accelerated particles in a neutral current sheet topology is:

$$N(E_k) = 1.47 \cdot 10^7 \left(\frac{nL^2}{BE_{k*}}\right) \left(\frac{E_k}{E_{k*}}\right)^{-1/4} \exp\left[-1.12\left(\frac{E_k}{E_{k*}}\right)^{3/4}\right] \qquad (3)$$

where $E_{k*} = 8.23 \cdot 10^{-3} B^2 (nL)^{2/3}$ $MeV$, $n$ - plasma density and $L$ - neutral current sheet length. In (16) *Pérez-Peraza et al.* demostrated that the source spectrum of the prompt component of three events, 23.2.1956, 7.12.1982 and 16.2.1984 may be adequately fitted by the relation (3) to the observational spectra provided the source parameters for the three events: $B = 30$, 20 and 20 $G$, $n = 2 \cdot 10^7$, $2 \cdot 10^6$ and $5 \cdot 10^6$ $cm^{-3}$, $L = 10^{10}$, $2 \cdot 10^9$ and $2 \cdot 10^{10}$ $cm$, respectively. These values correspond to generation altitudes $\geq 0.5 R_{\odot}$ in the corona, and the accelerating electric field is in the range $\mathcal{E} = (U/c)B \sim 10^{-2} - 10^{-1}$ $V \cdot cm^{-1}$, where $U = v_A/18$, and $v_A$ is the Alfvén velocity. The accelerated particles leaving the source undergo focusing in the diverging magnetic field of the corona and the IMF producing a major collimated component, though some fraction undergoes simultaneous azimutal drift ($\sim 0.7$ $v_{\perp}$), which could be associated to the delayed arrival of particles generated in well connected events ($\sim 60^{\circ}$ $W$) as reported in (11).

According to the proposed scenario, the bulk of particles are generated in the flare volume or its vicinity (at coronal altitudes about $0.07 - 0.14$ $R_{\odot}$) and are ejected at the opening of a surrounding closed magnetic structure ("the magnetic bottle"). The acceleration of this component is carried out by the dissipation of local turbulence to a select number of particles able to undergo resonant interaction with the turbulence wave modes. In order to fulfill the resonant requirements (17) particles must have a relatively high initial energy, which is also necessary in order to overcome the Coulomb barrier during their "flight time" in the closed magnetic region. This entails the requirement of an injection mechanism to supply such kind of particles into the resonant stochastic process. Following (18) we assume monoenergetic injection, where all particles that are susceptible of paticipating to the acceleration resonant process with magnetosonic turbulence have an initial energy around $E_0$. In this case, according to (18), the source energy spectrum for a steady state situation is:

$$N(E_k) = \frac{q_0}{2} \left(\frac{a_f \alpha}{3}\right)^{-\frac{1}{2}} \left(\beta_0^{3/2} E_0\right)^{-1} \left(\frac{\beta_0}{\beta}\right)^{\frac{1}{4}} \left(\frac{E}{E_0}\right)^{\frac{1}{2}} \exp\left[-\left(\frac{3a_f}{\alpha}\right)^{\frac{1}{2}} J_f\right] \qquad (4)$$

where $q_0$ $(proton/MeV)$ is the injected flux, $\alpha(s^{-1})$ is the acceleration efficiency, $E_0$ is the injection energy, $E_k$ = kinetic energy, $a_f = (\alpha/3)(\bar{F} + 3/\alpha\tau)$, $\tau$ is the mean confinement time of particles in the acceleration region, $\beta$ is the particle velocity in terms of the light velocity, $\beta_0$ is the velocity cor-

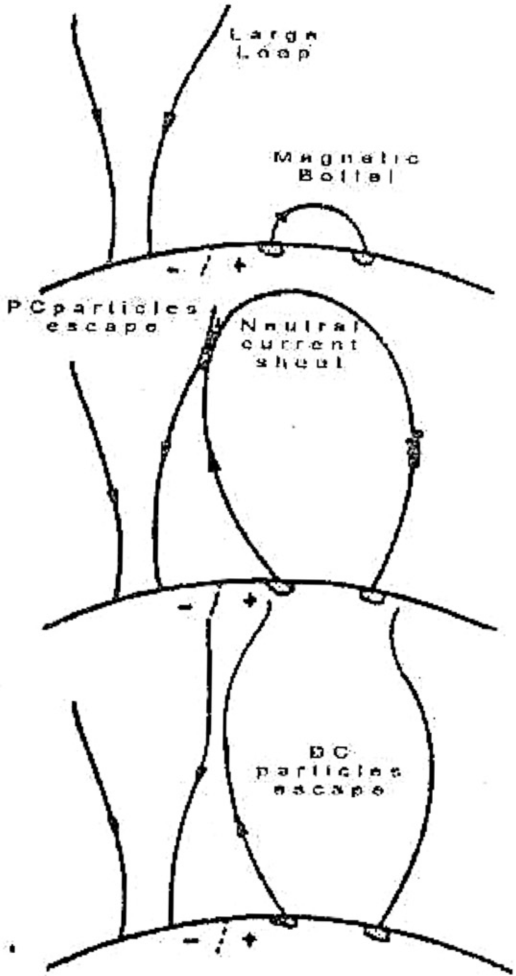


FIG. 6. Squematical drawing of the physical scenario proposed where the flare generated magnetic bottle expands and gets in touch with the extended coronal structure (large magnetic loop) and a neutral current sheet is formed.

responding to $E_0$, $\bar{F} = 0.5\left[\beta^{-1} + 3\beta - 2\beta^3 + \beta_0^{-1} + 3\beta_0 - 2\beta_0^3\right]$, and $J_f = \tan^{-1}\beta^{1/2} - \tan^{-1}\beta_0^{1/2} + 0.5\ln\left[(1+\beta^{1/2})(1-\beta_0^{1/2})/(1-\beta^{1/2})(1+\beta_0^{1/2})\right]$.

Calculated spectra with the equation (4) for the DC and observational spectra for the 29.9.89 and 22.10.89 events are shown on figs. 7.a) and 7.b), respectively. The best fits assuming monoenergetic injection at $E_0 = 1\ MeV$ and $\tau \simeq 1\ s$ are obtained in the range $\alpha = (0.03 - 0.037)\ s^{-1}$ for the first event and $\alpha = (0.034 - 0.065)\ s^{-1}$ for the second one. It should be noted that the fit was carried out without taking into account a possible interplanetary modulation of the observational spectra.

## CONCLUSIONS

On basis to the observational data summarized in the beginning of this paper, we discuss here a qualitative scenario for a particular kind of solar events in which two relativistic components seem to proceed from two differ-

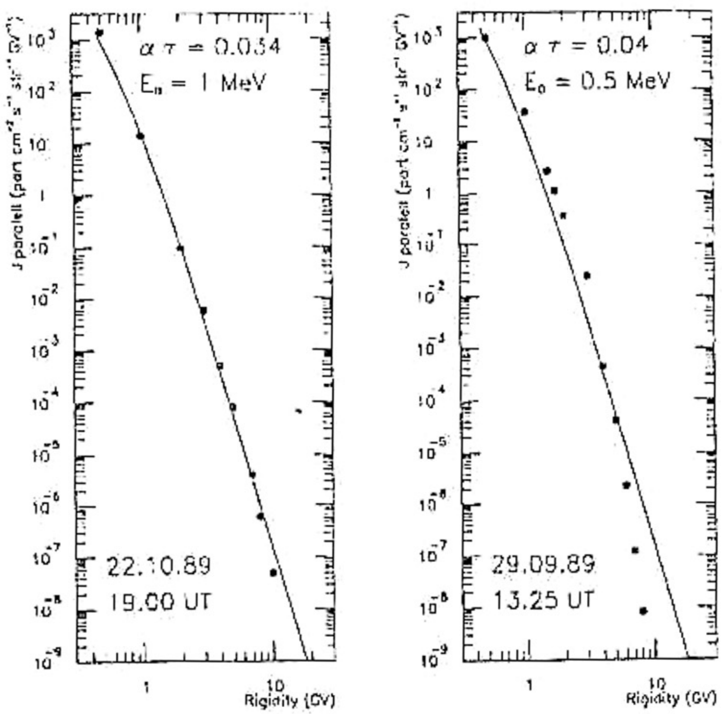


FIG. 7. Rigidity proton spectra of the delayed component of September 29, and October 22, 1989 events.

ent sources. One of them produces relativistic particles during the impulsive flare phase, deeply inside the corona, that we have designated as the delayed component; and another one operates later in the upper corona, where the conditions of particle escape are relatively easy, allowing particles to drift azimuthally through the corona and namely the prompt component because the first particle arriving to the Earth enviroment correspond to this population. Hence, during the development of the event both sources can contribute to a superposition of the observed fluxes.

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. In (16) it was shown that the energy spectra of the prompt component may be satisfactory reproduced assuming impulsive acceleration in a neutral current sheet. Here we have shown that the delayed component spectra may be satisfactory reproduced assuming stochastic acceleration by MHD turbulence. The source parameters for fitting the theoretical to the observational spectra turn to be within the order of the high and low coronal values, respectively. Similarly, the acceleration parameters range within the order of values inferred in other works on basis of the secondary radiation of flare emissions.

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