Solar Particle Source Energy spectrum: Stochastic acceleration *vs* Neutral Current Sheet acceleration *vs* Shock Wave acceleration

J. Pérez-Peraza[1], A. Gallegos-Cruz [2], L.I. Miroshnichenko[1,3] and E.V. Vashenyuk[4]

[1] **Instituto de Geofísica, Universidad Nacional Autónoma de México,** Ciudad Universitaria, Coyoacán, 04510, México, D.F., MÉXICO
[2] **UPIICSA, I.P.N.,** Depto. de Ciencias Básicas, Té 950, Iztacalco, 08400, México D.F., MÉXICO
[3]**N.V. Pushkov Institute IZMIRAN,** Moscow Region, 142190, RUSSIA
[4]**Polar Geophysical Institute,** Apatity, Murmansk Region, 184209, RUSSIA

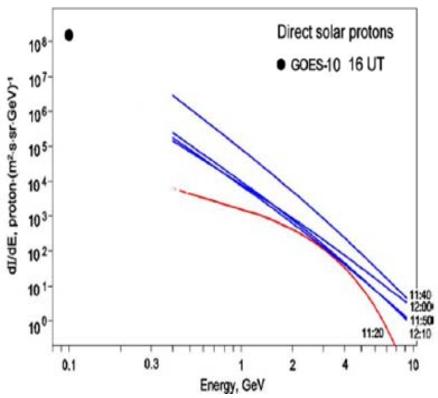
E-mail: ***perperaz@geofisica.unam.mx***

Abstract: It has been shown in a series of works that some Relativistic Solar Particle (RSP) events are composed of two different relativistic populations, a Prompt Component (PC) and a Delayed Component (DC), each one with different energy spectrum behavior. The source spectra of the DC tend to be an inverse power law at the steady state situation, whereas the spectra of the PC are considerable deviated from such a power law. Here we attempt to reproduce the observational spectra of the PC and the DC on terms of different scenarios: (i) DC acceleration from magnetic merging in a Magnetic Neutral Current Sheet (MNCS), (ii) Stochastic acceleration of an injected population pre-accelerated in a MNCS, (iii) Stochastic acceleration with monoenergetic injection, (iv) Stochastic acceleration with monoenergetic injection, while undergoing adiabatic deceleration. We contrast our results with those assuming Shock Wave Acceleration. Results are illustrated for the case of the September 29, 1989, July 14, 2000, October 28, 2003 and January 20, 2005 Ground Level Events (GLE`s).

INTRODUCTION

Up to present the worldwide neutron monitor (NM) network is the best way to detect relativistic solar protons (RSP) in Ground Level Events (GLEs) Such a detector network may be used as a unit multidirectional instrument that under adequate modeling techniques and a suitable computational code for particle trajectories in the magnetosphere, the parameters in the interplanetary space of relativistic solar proton events may be derived [1,2] : dynamical changes of the spectrum, pitch-angle distributions (PAD) and anisotropy in successive moments of time, together with their time profile reveals the existence of two distinct RSP populations, a prompt component (PC) characterized by an impulse-like intensity increase, rigid spectrum and high anisotropy, followed by a delayed component (DC) presenting a gradual increase, soft spectrum and low anisotropy. In general, the observational spectra at the early stage of the events are hard, just at the time when the PAD in events are the most narrow: as the PAD widen with time the spectra become softer giving a very peculiar exponential energy dependence, but as time elapses the spectra gets gradually steeper, up to the moment they reach the steady-state (1st figure). The existence of two different components in RSP has been proven by Vashenyuk et al in a number of works, for several GLEs of the previous Solar Cycles, and it is not the matter here to consider such an observational work. Rather, what we want to study is the faculty to reproduce the energy spectrum by the different acceleration processes, usually associated to the generation of solar relativistic particles, namely, (1) Shock Wave Acceleration, (2) Stochastic Fermi-type acceleration and (3) Direct Electric Field acceleration. We show here that the later two cannot be disregarded with respect to shock acceleration (that has gained high relevance in association with CME), but on the contrary, they can describe the Energy Spectra of both components of RSP events, the prompt and the delayed, that up to now no other process do it.

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 GEOS-10 at 16:00 UT



THE ACCELERATION SCENARIOS

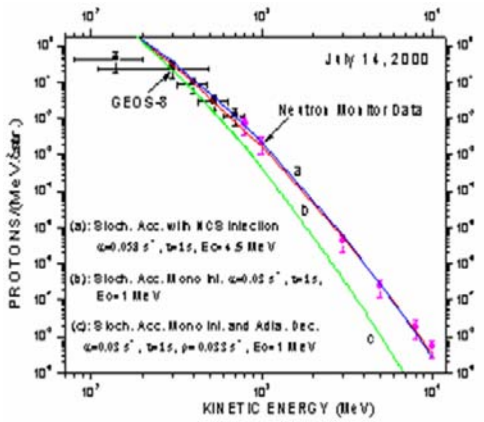
Direct Electric Field acceleration in a Magnetic Neutral Current Sheet (MNCS): Analytical steady-state energy spectra of solar protons accelerated in (MNCS) in solar flares were derived in [3] for 2-D topologies.

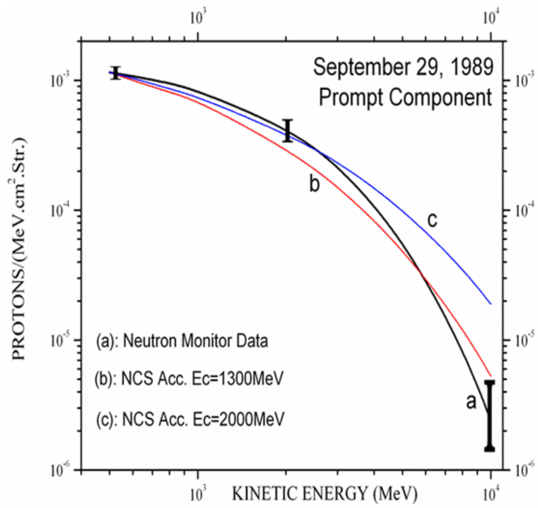
For stochastic acceleration spectra we use here the analytical solution of the Fokker-Planck type equation in energy phase space as given in [4,5]. This spectrum is valid in all the energy range, from non relativistic energies up to ultrarelativistic energies, including the transrelativistic domain. For a given turbulence Diffusion Coefficient, the basic free parameters are the acceleration efficiency, the adiabatic cooling efficiency and the mean confinement time, α, ρ and τ respectively. Though several kind of turbulent waves are susceptible of co-exist in the flare plasma their plausible energy source is still a controversial matter. We assume here the fast MHD mode. For the acceleration scenario we consider three possibilities - (1) Secular acceleration by means of Impulsive acceleration in a MNCS, from the source thermal matter – (2) Stochastic acceleration with a supra-Alfvenic monoenergetic injection energy Eo,, either with or without adiabatic deceleration, and (3) Stochastic acceleration with a realistic injection by preacceleration in a MNCS, with a well-defined spectrum, which spectral formulation was given in [4].

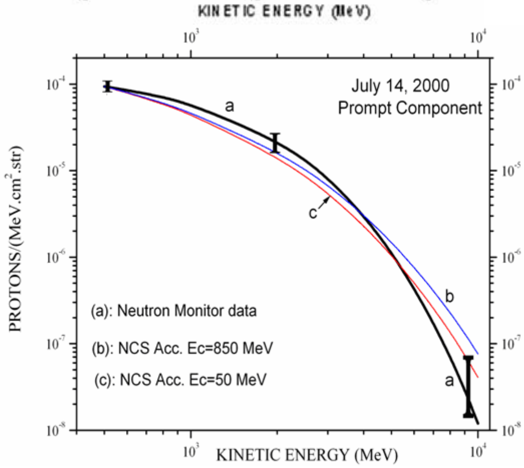
Theoretical Source Spectra VS observational Spectra. The direct confrontation carried out by many authors of theoretical source spectra to observational spectral, ignoring transport effects on the particle fluxes, is mainly based on the following arguments: - We are dealing with relativistic protons which practically do not feel interplanetary magnetic structures. - Fluxes are considered at the time of maximum intensity t_m - Many events occur in well connected sun-earth flares, and for those which are not, a model dependent assumption is considered by means of a closed expanding coronal magnetic structure connecting particle fluxes with the 60º W sun-earth magnetic field lines.

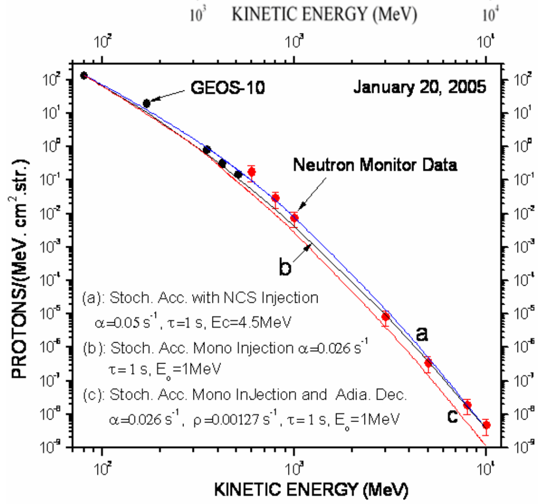
Concerning shock acceleration two outstanding works have to be mentioned here : in [6] the derived energy spectrum is unable to fit the relativistic high energy data from Neutron Monitor data of the September 29, 1989 event, or, if it is fitted, then it does not fit the transrelativistic energy range. In [7] it is shown for the specific case of the Bastille day event that the spectrum is best reproduced with stochastic acceleration by means of the formulation given in [4] than with shock acceleration Both works only deal with the Delayed Component. On 2^{nd} to 8^{th} figures we show the fitting of the spectra of both components the DC and PC for the events of 14.07.2000, 29.09.1989, 20.01.2005 and 28.10.2003. Analysis of these figures show that adiabatic acceleration does not was important for these events, indicating that acceleration was relatively high and the expansion velocity quite low. It can bee seen also that the best fit is systematically obtained when the injection is with a well defined pre-acceleration spectrum from a MNCS and not with monoenergetic injection. We illustrate for two events the fitting of the prompt component with acceleration from thermal energies in a MNCS. It can be seen that within the error bars, the spectra is well reproduced. The last two figures show the time-dependent spectrum for the 28.10.2003 event at an acceleration time of 10 s when the steady-state is not yet reached and at 20 s when it is reached.

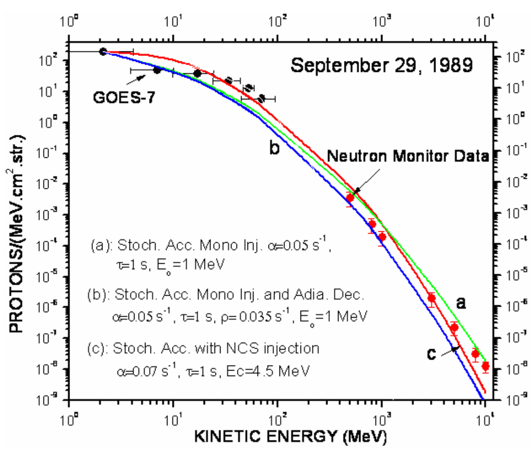
ICRC 2007 Proceedings - Pre-Conference Edition

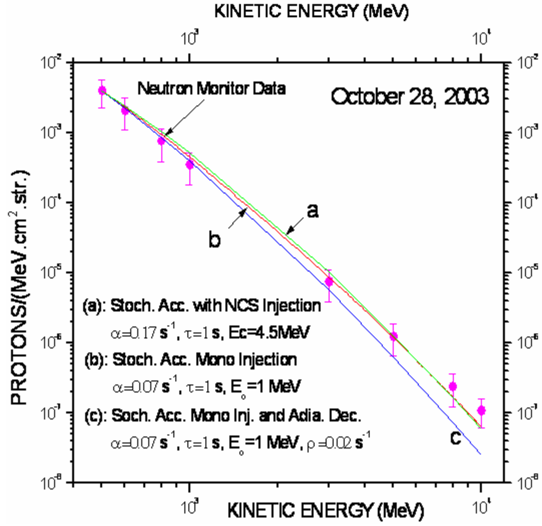

July 14, 2000
GEOS-8
Neutron Monitor Data
(a): Stoch. Acc. with NCS Injection
(b): Stoch. Acc. Mono Inj.
(c): Stoch. Acc. Mono Inj. and Adia. Dec.
PROTONS/(MeV.cm^2.str.)
KINETIC ENERGY (MeV)

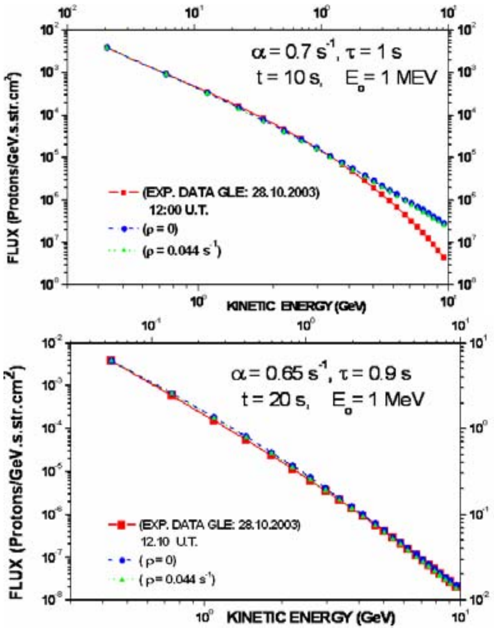

September 29, 1989
Prompt Component
(a): Neutron Monitor Data
(b): NCS Acc. Ec=1300MeV
(c): NCS Acc. Ec=2000MeV
PROTONS/(MeV.cm^2.Str.)
KINETIC ENERGY (MeV)


July 14, 2000
Prompt Component
(a): Neutron Monitor data
(b): NCS Acc. Ec=850 MeV
(c): NCS Acc. Ec=50 MeV
PROTONS/(MeV.cm^2.str)
KINETIC ENERGY (MeV)


GEOS-10
January 20, 2005
Neutron Monitor Data
(a): Stoch. Acc. with NCS Injection
α=0.05 s^{-1}, τ=1 s, Ec=4.5MeV
(b): Stoch. Acc. Mono Injection α=0.026 s^{-1}
τ=1 s, E$_o$=1MeV
(c): Stoch. Acc. Mono InJection and Adia. Dec.
α=0.026 s^{-1}, ρ=0.00127 s^{-1}, τ=1 s, E$_o$=1MeV
PROTONS/(MeV. cm^2.str.)
KINETIC ENERGY (MeV)


September 29, 1989
GOES-7
Neutron Monitor Data
(a): Stoch. Acc. Mono Inj. α=0.05 s^{-1},
τ=1 s, E$_o$=1 MeV
(b): Stoch. Acc. Mono Inj. and Adia. Dec.
α=0.05 s^{-1}, τ=1 s, ρ=0.035 s^{-1}, E$_o$=1 MeV
(c): Stoch. Acc. with NCS injection
α=0.07 s^{-1}, τ=1 s, Ec=4.5 MeV
PROTONS/(MeV.cm^2.str.)
KINETIC ENERGY (MeV)


Neutron Monitor Data
October 28, 2003
(a): Stoch. Acc. with NCS Injection
α=0.17 s^{-1}, τ=1 s, Ec=4.5MeV
(b): Stoch. Acc. Mono Injection
α=0.07 s^{-1}, τ=1 s, E$_o$=1 MeV
(c): Soch. Acc. Mono Inj. and Adia. Dec.
α=0.07 s^{-1}, τ=1 s, E$_o$=1 MeV, ρ=0.02 s^{-1}
PROTONS/(MeV.cm^2.str.)
KINETIC ENERGY (MeV)



THE TWO-SOURCES MODEL

The scenario for the RSP events is based on two different sources of particle acceleration: it is proposed that the delayed component is generated in the flare volume at a height of ~ (0.07-0.20)R_s (where R_s is the solar radius) and ejected after 30 min-2 hrs. from the beginning of the acceleration, at a certain height reached after this time with a transient velocity (bottle or shock front) of ~ 400-3800 km/s. Concerning the source of the prompt component, the fact that particle ejection is highly abrupt (coronal storage time ≈ 0) and particle flux is highly anisotropic (sharp intensity rise and rapid decay) points toward a source associated with open field lines (rapid particle escape) high in the corona, where particles are efficiently accelerated by a deterministic process, and rapidly collimated through the IMF lines. Such acceleration may occur during magnetic merging between the expanding magnetic bottle and coronal field lines of opposite polarity (e.g., coronal loops, arcades or helmet streamers) 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.

CONCLUSIONS

We have shown that energy spectra of the PC in RPS events with two distinct populations can be adequately reproduced by an exponential type spectrum from MNCS acceleration. For the case of the DC component the spectra may be adequately reproduced by stochastic acceleration, and that under conditions of very low acceleration efficiency adiabatic losses may contribute to shape the spectrum, which is not the case of the four events in consideration. We have also shown that a realistic injection spectrum from a pre-acceleration in a MNCS into the stochastic acceleration process reproduces better the observational spectrum that under the conventional assumption of a monoenergetic injection. It should be emphasized that in reproducing the PC and DC spectra the derived source and acceleration parameters from our fittings are within the realistic values expected in the coronal flare.

Finally, it is worth mentioning that the presence of CME indicates the possible production of RSP in a shock acceleration process, as has been suggested by many authors,. Though this is undoubtedly a process that is present, we believe that it gives only a certain contribution to the low energy part of the spectrum, which probably mix with the bulk of particles of the DC population . Our argument is based on the fact that shock acceleration fits rather the low energy region. On the other hand, to our knowledge up to now shock acceleration does not explain the PC.

References

[1] Vashenyuk, E.V., Miroshnichenko, L.I., Sorokin, M.O. et al., Adv. Space Res. 14, 711, 1994.

[2] Vashenyuk, E.V., Miroshnichenko, L.I., et al., Proc. 25th ICRC., Durban, South Africa, 1, 161, 1997.

[3] Pérez-Peraza J, Gálvez M., and Lara R. Advances in Space Research, 18, 365-368, 1978.

[4] Gallegos-Cruz A. and Pérez-Peraza J.. Astrophys. J., 446, 400-420, 1995.

[5] Perez-Peraza J., Gallegos-Cru z A.Vashenyuk E., Adv. Space Res. 38, No.3, 418-424, 2006.

[6] Berezhko and Taneev, Astron .Letters 29-8, 530-548, 2003.

[7] Bombardieri, D.J. et al, Ap. J. 644,. 565-574, 2006.