Acceleration of Solar Particles during cycle 22

J. Pérez-Peraza

Instituto de Geofísica, U.N.A.M., C.U., Coyoacán, 04510, México, D.F., MEXICO,

Abstract

The scenarios for the production of Solar Energetic Particles (SEP) and the features of the relevant acceleration mechanisms are reviewed. Emphasis is made on two main kind of processes: deterministic (secular) and stochastic processes. As for deterministic acceleration we discuss the magnetic *neutral current sheet topologies* that are most commonly associated to the flare phenomenon: a discrimination is made among them based on their ability for producing particles fluxes with typical solar particle spectra. For stochastic acceleration we analyze the most plausible *turbulent wave modes* which are able to accelerate particles in the solar atmosphere: a discrimination is made according to the involved time scales and the predicted energy spectra in comparison to observational data. On this basis, we discuss a plausible scenario for a particular kind of SEP events where two independent relativistic populations have been identified, particularly from data of some Ground Level Enhancements during Solar Cycle 22. The peculiar behavior of particle production in those events is reviewed, and an interpretation is given in terms of a *two-source* model.

Solar particle production.

The main features of solar particle production may be summarized as follows:

1) Occurs in association with Transient Energy Releases: Solar Flares and/or Coronal Mass Ejections (CMEs), which frequency varies proportionally to Solar Activity[1].
2) Not all Flares produce energetic particles, but Flares that accelerate particles can do it with or without associated CMEs [1].
3) Very few CMSs accelerate particles in the absence of Flares [1].
4) Around 1/3 of CMSs drive a collisionless shock wave able to accelerate particles up to high energies [1].
5) Acceleration of (SEP) takes place either as sporadic Events, from individual Flares & CMSs, or continuosly in series ("super-events") of Long-Lived Events and Corrotating Events, from multiple Flares & CMSs in a single Active Center [1].
6) Each individual event shows particular peculiarities, but according to common features most events can be classified in three categories[1,2,3]:

I. "Impulsive" or non-relativistic electron- ^{3}He-rich Events.
a) Low intense events producing non-relativistic ions and electrons.
b) High *electron /proton* ratio, with most energy carried by electrons.
c) Particles spread in a cone $\leq 30°$ around the flare site.
d) Frequency $\geq$ 1000/ year at Solar Activity Maxima.
e) Enhanced abundances of some heavy ions and ^{3}He/^{4}He ratios, varying from event to event.

f) Charge state of ions *favorizes* a flare plasma source ($T \geq 5 \times 10^6$ K).
g) Events are associated with Flares or Subflares but not with CMSs.
h) Duration of some hours.

II."Gradual"or large solar energetic particle events (LSEP).
a) Highly intense and energetic Events, including Relativistic particles.
b) Low *electron/proton* ratio, with most energy carried by Protons.
c) Particles spread in a cone ≤ 180° in coronal heliolongitude.
d) Frequency of few tens per year at Solar Activity Maxima.
e) "Typical Solar" heavy nuclei abundances and $^3He/^4He$ ratios.
f) Charge state of ions *favorizes* a quiet coronal source ($T = 1\text{-}2 \times 10^6$ K).
g) Events are associated with Flares and > 90% of cases with CMEs-driven Shock waves.
h) Duration of some days.
Most of the Ground Level Events (GLE), also known as Solar Relativistic Proton Events, (which frequency in the last 56 years is < 2/year) are included in this LSEP categorie.

III. Mixt (hybrid) events.
Those presenting both the gradual and impulsive features.

- Besides, the associated electromagnetic emissions (mostly radio, microwaves, optical, X-rays and γ- rays) and solar neutrons behave differently:the emission duration and the shape of their time profiles distinguishes quite clearly among the different kind of events.
- *Modelation* of SEP production is general done for individual events, so that a vaste amount of scenarios have been developed taking into account peculiarities of events and the behavior of the associated emissions.

Scenarios.
According to the *Amount of Traversed Matter X* (gr/cm^2) = ρvt (ρ, v, t are the density, particle velocity and confinement time respectively) scenarios are based on:
Thick target models (when ρ and/or t are relatively high): - particle trapping in closed topologies with strong converging magnetic fields and/or low corona (or chromospherical) densities - ρ can be low but t can be very long (closed magnetic topologies) - the energy spectrum is modified by collisions.
Thin target models (when ρ and t are relatively low): - acceleration in the high corona and free particle escape (open magnetic field topology) - energy spectrum is not altered.
To account for the abundance ratios, charge states and the associated radio, X-ray and γ-ray emissions, a vaste amount of scenarios, postulating combinations of Thick and Thin target models have been developed, either with *continuous* acceleration in 1- *phase*, or *episodical* acceleration in 2- and 3- acceleration *phases* with trapping between them[4].
- Often, acceleration phases are associated with a Thin target, followed by precipitation into an interaction region associated with a Thick target. However, full scenarios have

also been proposed within the frame of one of them, either the Thick or the Thin target geometry.

- One-*phase* acceleration is frequently associated to *Direct Electric field acceleration*, while 2- and 3- acceleration *phases* are rather associated with *stochastic* and *shock wave acceleration*.

- On the previous basis, Impulsive Events are better described in terms of acceleration by *stochastic turbulence*, whereas Gradual Events are usually explained by *shock wave acceleration* as well as by an *stochastic* or a *DC-field acceleration* process.

Here it is presented an scenario for an specific kind of *ground level events* which data (mostly during solar cycle 22) indicate the presence of two independent relativistic proton components.

Let us begin for giving a Brief *glance* on the status of *Solar Particle Acceleration Processes.*

Constraints for solar particle acceleration.

- Theories must explain, at least, the observational data on:

1) time scales of acceleration (risetime and duration).
2) particle energy spectra of diferent events.
3) number of accelerated particles (10^{32} - 10^{41}).
4) selectivity to describe the variability of electron/proton ratios and of ions and isotopic abundances.

- If acceleration is by wave turbulence, it is additionally required:

5) a plausible source for such turbulence.
6) stability of turbulence energy density (typically ~ 1-10 ergs/cm^3).
7) enough number of particle with a minimum energy above an "injection threshold" value (which may be a thermal or suprathermal one according the kind of involved turbulence).

Acceleration processes in the solar atmosphere.

Particle acceleration is ultimately due to the action of a direct or and induced electric field on charged particles. In terms of the nature of the process as particles gain energy, we can distinguish two kind of acceleration mechanisms[5]:

- Deterministic (secular) processes:

when particles gain energy systematically in an unidirectional form. The accelerating agent is general associated with macroscopical magnetic structures of cosmic plasmas.

-Stochastic processes:

when particles gain or loss energy in random small changes, but there is statistically a net energy gain. The accelerating agent is usually associated with wave turbulence. It is also known as Turbulent, Statistical or even Diffusive acceleration (at quasi-linear order may be described by a diffusion equation in momentum space).

Deterministic processes.

I. Direct electric field acceleration

1. Acceleration by perpendicular electric fields to the local magnetic field: stationary and time-dependent (1- 2- 3-dimensions) models:

a) 1-D (magnetic neutral current X-points and lines), 2-D (magnetic neutral current sheets) and 3-D (magnetic neutal current layers).

b) Loop Coalescence.

2. Acceleration by parallel electric fields to the local magnetic field.

a) Double Layer acceleration.

b) Acceleration by Current Inerruption in force-free magnetic flux tubes: inductive circuits as solar twisted loop-like ropes.

c) runway acceleration.

II. <u>Shock acceleration</u> (1st-order Fermi type acceleration).

1. (DSA) Diffusive Shock Acceleration (Turbulent-Scattering).

2. (SDA) Shock Drift Acceleration (Scatter-Free).

Stochastic processes.

Most "modern" works study stochastic processes within the frame of weak turbulence, in terms of resonant <u>wave-particle</u> or <u>wave-wave-particle</u> interactions by means of the resonant condition: $\omega - S\Omega - k\,v = 0$.

I. Cherenkov (Landau-Damping) acceleration: resonance between the wave phase velocity V_ϕ and the particle velocity v: $v\ /\Omega < 1$; $\omega << \Omega$; resonance at $S = 0$

1. 2nd-order Fermi type acceleration: damping of the electric field of waves[10].

2. Magnetic Pumping (Betatron) acceleration:compression and dilatation of the magnetic field[8].

3. Transit time Acceleration (called Magnetic Landau-Damping) : damping of the Magnetic field of waves[10].

II. Gyroresonant Acceleration: resonance between the wave frequency and the particle gyro- frequency. $\omega/k\ v << 1$; $\omega \geq \Omega$; resonance at harmonics $S \geq 1$.

III. Non-linear Landau-Damping and Non-linear gyroresonant acceleration.

- Acceleration by a collection of weak double layers and DSA by a collection of weak shocks can be treated as a kind of stochastic acceleration[6].
- Stochastic processes has been widely discussed in the literature in connection with the following kind of Turbulence:

<u>Wave turbulence</u>: In a cold plasma of Hydrogen the most common turbulence can be reduced to two groups (Tables 1 & 2):

<u>Electrostatic modes</u>		<u>Electromagnetic modes</u>
- Langmuir waves		- MHD turbulence
- Lower Hybrid waves		Alfvén waves
- Ion Sound waves	<==========>	Slow Magnetosonic waves
- Ion Cyclotron quasi-parallel waves		Fast Magnetosonic waves
- Ion Cyclotron quasi-perpendicular waves (Bernstein modes)		Hybrid modes
- Whistler waves		

TURBULENCEE TYPE	CHERENKOV ACCELERATION $(\omega < \Omega)$ $s = 0$	GYRORESONANT ACCELERATION $(\omega \geq \Omega)$ $s \geq 1$	LIMITATIONS
MHD: Alfven Mode $(\omega << \Omega_H)$	Within this scheme resonance is very weak and then the acceleration is not efficient[7,15] .By non-linear Landu-damping[22] may accelerate electrons up to $v > v_A$.	Protons: from suprathermal energies up to GV in times $1s \leq t \leq 10s$ [12, 13]. Electrons: it is required injection energies > 940 MeV, by non-linear and cascade effects[22] can reach ~ 30 MeV from ~ E_{alfv}. If $\omega \rightarrow \Omega_H$ injection is negligible[21].	For protons it is required an injection process that raise their energy up to a threshold energy and turbu-lence levels ~ 10 erg/cm^3. Electrons with this energy practically do not exist in the solar corona.
MHD: Fast Mode $(\omega << \Omega_H)$ Under Cascading effects $(\omega \rightarrow \Omega_H)$	Widely used for studies of particle acceleration, often with a constant efficiency $\alpha(E,t,k)$[17,18,19,20]. Turbulent levels ≥ 10 erg/cm^3 are required. Cascading effects can shift the frequency spectrum, increasing the acceleration efficiency[21] .	Protons: energy > 940 MeV $(\gamma > 1)$ is required. Electrons: $\gamma > 1840$ is required for interaction with waves in the high frequency limit $(\omega \geq \Omega_H)$; and more energetic electrons to interact with lower frequencies of the spectrum[39].	Protons need injection at $E_{Alfv} >> E_{Therm}$ in the solar corona. - The amount of accelerated protons is less than in observational data. Non-linear interactions may solve this problem[22,25] if turbulence develop to 10^3 $ergs/cm^3$ in ~ 0.15 s [39].
MHD: Slow Mode $(\omega << \Omega_H)$	This mode is quickly damped in the corona from dissipation by non-resonant processes before it can accelerate particles. Under conditions of the solar chromosphere it may lead to particle acceleration [32].	The required level of turbulence and the threshold values for this kind of acceleration are much higher with this mode than with the fast mode. Non-resonant damping dissipates energy quickly.	It is required turbulence levels higher than those expected within the solar corona($>10^3 ergs/cm^3$):thermal dissipation processes inhibit waves to reach those values.

TURBULENCE TYPE	CHERENKOV ACCELERATION ($\omega < \Omega$) $s = 0$	GYRORESONANT ACCELERATION ($\omega \geq \Omega$) $s \geq 1$	LIMITATIONS
WHISTLER TURBULENCE TYPE ($\Omega_H < \omega < \Omega_e$)	Due to $\omega > \Omega_H$, this acceleration type is out of context.	May be generated by a shift in frequency of the fast MHD mode. The resonance requirement $\omega \geq s\,\Omega/\gamma$ and $\gamma > 1$, $\Rightarrow$ protons cannot be accelerated. Acceleration of thermal electrons requires a flux of electrons with E > 20 KeV[23] . Whistler are used for isotropization during acceleration[17,24].	This turbulence itself can not accelerate thermal electrons in the solar corona : the threshold injection energy is $v > 43V_A$.
LOWER HYBRID TURBULENCE ($\Omega_H << \omega << \Omega_e$)	Due to $\omega > \Omega_H$, this acceleration is out of context.	Generated by cross-field ion motion o relative electron-ion drift. Evoked for acceleration of ions in the high corona[25,37].	Wave source requires of turbulent shock fronts with a thin and a thick where waves can grow[37].
CYCLOTRONIC TURBULENCE TYPE ($\omega \geq \Omega$)	Due to $\omega \geq \Omega_H$, this acceleration type is out of context.	This turbulence type is generated around the cyclotron resonance. Two cases are has been considered: ($k_{11} >> k_\perp$) and ($k_\perp >> k_{11}$) cyclotron waves (called Berstein modes)[10,15,33]. They were evoked for ion acceleration, to explain overabundace of helium isotopes [26].	Generation of this turbulence in the solar corona requires the presence of jets of supra-thermal particles.
LANGMUIR WAVES phase velocity ($V\phi = \omega/\kappa$) $V_{te} << \omega/\kappa << c$	Widely study in the context of particle acceleration[26,27,28]. Plausible sources: alteration of plasma neutrality.	Can be very efficient for acceleration of non-relativistic electrons[28]. Two-stream instability is often evoked as turbulence source, streaming of electrons, current-drive instabilities, etc.	The basic problem is their generation and short mean life[30,38].

MHD turbulence is often worked for acceleration of non-relativistic ions and relativistic electrons within the frame of:
a) The Çherenkov acceleration ($S = 0$; $p_\perp =$ Cte) within the frequency regime $\omega << \Omega_H$ $\lambda >> r_g$)[7].
Landau damping is inefective for Alvén waves, affects rather the compressed component (fast mode) of MHD turbulence[6].

- 2nd-order Fermi acceleration[8].
- Transit time acceleration[9,10].
- Magnetic Pumping acceleration[10,11].

b) The gyro-resonant acceleration ($S \geq 1$; $p_\perp \neq$ Cte.), wilthin the frequency regime $\omega \geq \Omega_H$
($\lambda >> r_g$) [12,13]. Can be highly effective for Alfvén waves.
c) The non-linear Landau damping (wave & wave-particle), and the non- linear gyroresonant wave damping[10,14].
Low Frequency Electrostatic waves are usually worked for acceleration of non-relativistic electrons within the frame of:
a) Landau wave damping.
b) Gyro-resonant wave damping.

- According to work[2] recent observations indicate that all mechanisms, Direct Electric Field acceleration, Shock acceleration and Stochastic acceleration may all be operating in flare-phenomena, with ions and electrons being accelerated together even simultaneously during any phase of an event.

- In spite that most of Direct Electric Field acceleration processes do act efficiently at laboratory scale (mainly in linear and toroidal confinement experiments), and that plasma turbulence and shock waves are common features of nature and can be reproduced at laboratory scale, all the proposed acceleration processs are still a matter of polemic work, and most of them has been objected on theoretical grounds:

♦ Arguments against shock acceleration in connection with flares are for instance: Scatter Free-Shock Drift Acceleration (SDA) in a single crossing of the shock front can only increase the particle energy by at most a factor of 2.5. While Diffusive Shock acceleration (DSA) by scattering of particles in the turbulent upstream and downstream lead to a large energy increase because every shock crossing leads to an energy gain, however, DSA is efficient only for those Gradual events where the shock can develop in a time < 0.1 s, provided particles have velocities higher than the mean square velocity of the turbulent scatters[16]. Also, DSA may be no effective in the low corona because of the high hydromagnetic velocity (low Mach number). - Nevertheless, since Gradual events are associated with CMEs (which drive the coronal shocks) and DSA can reproduce the single power law-rigidity spectra observed with low energy electrons in Gradual events, DSA remain a very promising process in the high corona: to know the real accelerating efficiency, the energy density level of the sacattering turbulence needs to be determined.

♦ direct Field Acceleration depends strongly in the existence of anomalous resistivity during the time scale of the phenomenon, while runway acceleration is strongly inhibited by self-inductance. It is argued that due to current interruption (necessary for developing anomalous resistivity) the number of accelerated electrons falls below obsevational values. In particular, reconnection in neutral current sheets (NCS) is often objected in connection with a poor particle escape into the interplanetary space. However, it should be noted that in work[40] it has calculated the trayectories of particles in NCS and shown that most of particles are able to escape, though the degree of scape depends on the magnetic fiel topology of the sheet. Further arguments supporting NCS has been widely discussed in works[34,35,36].

♦ The bigest problem that Stochastic Acceleration confrontates is that, there is no direct observational evidence of the level of turbulence and mean-life of both, Low Frequency Electrostatic waves and MHD turbulence, during the flare phenomena. By the moment, what we can do is to derive the conditions that need to be satisfied in order for stochastic acceleration to be effective. - Though physical concepts date from more of 5 decades, big advances are continuously reached in the task of delimiting the efficiency conditions for stochastic acceleration.

Generation of MHD turbulence may occur when a macroscopic system supported by magnetic stress becomes unstable, as well as during merging processes in reconnecting current sheets. So, it is expected that its presence is widely spread in the solar atmosphere.

- On this basis, since CMEs in Gradual events are associated with driving coronal shocks, setting up: - reconnection - turbulence - opening magnetic field lines, so, the scenario dicusssed in the end part of this review, in connection with GLE presenting two-relativistic-componets, has been developed in terms of Stochastic (Turbulent) acceleration and Neutral Current sheet acceleration.

Since gyroresont acceleration by Alfvén waves is marginally less efficient[6] than Cherenkov acceleration by the fast mode wave, for the stochastic acceleration stage of the two-step-scenario discussed hereafter, it will be evoked acceleration by Landau-damping of the fast MHD mode:

- In work[41] it is delimitated the turbulence levels and time scales under which such a kind of acceleration by the fast mode can overcome non-resonant thermal dissipation processes and Coulomb collisional losses in the solar corona in order that acceleration be efficient. To overcome the deficit of accelerated protons we assume that the injection energy can be reduced to $E \leq 1.5kT$ on basis to the non-linear and cascade effects discussed by Miller & co-authors[21,22,23,31,39].

- In works[42,19] we studied the energy spectra and time scales for acceleration of protons as predicted by Cherenkov acceleration: according to the quasi-linear approach, stochastic acceleration can be described by statistical equations (e.g. Schlickeiser[43]) from which a Fokker-Planck type equation may be derived. We solved a *particular* case of that equation and derived analytical spectra for the whole energy range, including the transrelativistic domain that up to then had been only worked out by numerical methods. Energy spectra and time scales are in agreement with the numerical results of others authors what, leads us to - consider this approach for modeling two-relativistic component-GLE - (see Figs. in Ref. 42).

Neutral Current Sheet acceleration in solar flares has been widely discused and reviewed[44] in the literature since the days of Giovanelli and Dungey. In order to discriminate between the wide variety of NCS topologies proposed for solar flares, we have derived the energy spectrum of particles which is produced in each topology[45,46] (see Table of topologies, parameters and figures in works[45,46]) andwe had found that, the only one that can reproduce observational spectra up to 1 GeV in realistic conditions of anomalous conductivity of the flare plasma is the NCS topology proposed in the model of work[47]. - We use this topology for modelation - .

Production of solar relativistic particles as studied at ground level.

The study of Solar Cosmic Rays (SCR) at relativistic energies (E > 500 MeV for protons) provides a usef ul tool for understanding the processes of their generation, because: - 1) can be detected at Ground leves, (GLE), so gives good permanent source of information at long term. - 2) helps to estimate some parameters of solar particle accelerators as for instance, upper energy limits and times of ejection. 54 GLE have been registered in half a century, since the first Ground Level measulrements in 1942 up to 1992, from which 15 in the current solar cycle. In the last two decades a number of essentially new results on temporal, spectral and pitch-angle distributions of SCR at the earth's orbit and near the Sun have been obtained, e.g., the instants of SCR ejection and their arrival to the earth were evaluated with an accuracy of 1-5 min[48]. Based on high temporal resolution data of neutron supermonitors and a neutrino detectors during the present solar cycle, some peculiarities of GLE have been observed:

- the frequency of the events in 1989-1992 was four times the average for the whole SCR observation period (~ 1 $year^{-1}$).
- the high energy cutoff of SCR greatly exceeds the regular values of ~ 5 GeV that had been determined in[49] for GLE of the period 1942-72.
- the form of the temporal profiles of some events distinguishes by a two-hump structure.
- some of the ejections are burst-like of short duration (≤ 15 min) with a strong anisotropy.

In particular, the two last features will be analyzed here:

Observational data of relativistic SCR.

- Comparison of properties of intensity-time profiles, energy spectra and anisotropy of SCR as measured by different neutron monitor stations during the same event:

♦ *Intensity-time profiiles* contain infomation about the time of SCR ejection, its duration, and transport through the corona and interplanetery space. - Typical profiles of GLE register by high-latitude NM stations may be separated in two groups: "prompt" and "delayed" events, with narrow (sharp) and broad (smooth) prof iles, respectively. - Among the peculiarities of GLE in solar cycle 22 is that in some events, NM stations, well connected with the solar sources, are able to detect both sharp and scattered peaks:

- prof iles of the GLE series of May 21-22, 1990 display a distinctive two-peak structure at the stations with ccutoff rigidity R_C = 0.57 - 1.84 GV (Fig. 2 in Ref. 50). - Profiles of the October 22, 1989 GLE show that stations at the north hemisphere (Apatity & Oulu) only detect the 2nd peak, but South Pole station in the south hemisphere, in well connection with the flare site 27 S - 32 W, detected both components (Figs. 1 in Refs. 50,51,52). - Despite the great variability of profiles at different stations during the September 29, 1989 GLE due to anisotropy effects, two main components of the SCR intensity may be distingushed (Figs. 2 in Ref. 52,53,54,55, Fig. 1 in 56 & Figs. 1,4 in 57).

♦ *Energy spectra* of SCR contains information about the acceleration process and the physical parameters of the source. The observation of two different components of solar relativistic protons is not new: long ago[58] had been reported that the biggest GLE of February 23, 1956 presents a *"direct radiation fraction"* with a harder spectrum than that of the *"deflected fraction"*. - Abnormally hard spectra have also been recorded for other GLE, e.g. May 7, 1978, Februry 16, 1984 (see Fig. 3 in Ref. 59 & Figs. 3-5 in 60) - During solar eycle 22, work[61] reported rigidity spectra with different slope at different times of a single GLE, the harder and the flatter ones coinciding with the Ist and 2nd peaks of the corresponding profiles respectively, (with a 1-hour difference approximately): the September 29, 1989 and October 22, 1989 GLE's (Figs. 1 in pg. 48 & Fig. 2 in pag. 53 in Ref. 61).

♦ *Anisotropy* of relativistic SCR gives information not only of the ejection from the source, but also of the state of the interplanetary medium and so, of the propagation conditions; according to work[62] if an equilibrium exists between the processes of scattering and focusing in the interplanetary space (i.e. if the inteplanetary conditions do not change significantly during the time of a SPE development) then the pitch angle distribution in the SCR flux will be retained in the course of particie transport from the Sun to the Earth. - A plot done in work[63] for the November 18, 1986 GLE, showing the dependence of the SCR intensity at different NM stations on the angular distance of their mean asymptotic directions from the anisotropy axis at $\theta = 0$ (points A & B in Fig. 4 in Ref. 51& Fig. 3 in 52) leads to averaged profiles (A & B in right side of those Figures) which correspond to an anysotropic component (points near O° in the box of the upper left side) and an isotrpic one (increases scattered for more of 80°), and the time shift between their onsets is nearly the same as between maxima, seeming to indicate that profiles A & B correspond respectively to a "prompt" & "delayed" components of the Nov. 18, 1986 GLE. This situation is found in many GLE, and in all these cases one cannot always identify any suitable shock or any other reflecting boundary behind the earth' orbit able to produce the scatered component, as is has been often speculated in the literatura. The anisotropy charcteristics of both components in all those events may reflect the properties of two differnt sources at the Sun: the "prompt" component (PC) must have an anisotropic source (located in a place where field lines are rather open, allowing fast particle escape, and channeling them in narrow azimuthal extensions, probably in the high corona), and the "delayed" componen (DC) in rather an azimuthally extended source, where magnetic turbulence is high enough to provide an scattered flux at the ejection (probably in the main flare body itself, where magnetic confinemnet is more efficient). Summarizing, observational data show that some SPE are characterized by two independent ejections of relativistic protons, whereas others SPE only present the "scattered-isotropic" (DC) component, or, only the anisotropic (PC) ejection.

- *While these observational evidences are* necessaries *may not however be* sufficients, *therfore, some alternative techniques of data analysis have been applied*[51,52].

Method of data analysis (I):

vT - Technique[67]

1) total distance travelled by the bulk of particles from the source to the detector:

$$vT_m = A_m + B_m v \quad [1]$$

2) total distan travelled by the "first" particles from the source to the detector:

$$vT_0 = A_0 + B_0 v \quad [2]$$

T_m : time of maximum intensity (arrival of the bulk of particles).
T_0 : time of arrival of the first particles (onset time).
A_m : path of the bulk of particles through the IMF.
A_0 : path of the onset particles through the IMF.
$B_m v$: path of the bulk of particles in the corona.
$B_0 v$: path of the onset particles in the corona.
B_m : time spent by the bulk of particles in the corona.
B_0 : time spent by the onset particles in the corona.

times are reported relatively to type II radiobursts ~ FSMP (Cliver et al[48]).

(1) For the <u>bulk population</u> (vT_m - analysis) we found that:

- comparison of data with equation [1] for the events of cycle 21 shows that 3 of them contain a DC characterized by B_m = Const., i.e., all particles of any energy spend the same time in the corona (2.1, 1.8, & 1.7 hrs. respectively) ((Figs. 2 in Refs. 57, 65, 66)
- one of them (the Dec. 7, 1982 GLE) contains two components, the delayed one (including electrons) and a prompt one characterized by $B_m \approx 0$ (coronal storage time close to 0); the Feb. 16, 1984 GLE consists of the PC alone.
- for two events of cycle 22, the same vT_m plots show that they present both components, DC & PC, even in the non-relativistic range: particles of the sharp peaks (PC) have shorter path ($vT_m \sim 2 - 3$ AU) than particles of the scattered diffusive peaks (DC), $vT_m \sim 7$ AU (Fig. 3 in Ref. 51 &Figs. 5,6 in 52).

(2) for the onset population (vT_0 - analysis):

- the time spent in the corona is obtained by substracting from the arrival time of the "first" particles the minimum sun-earth propagation time of ~ 11 min[48]:

$$B_0 = T_0 - 11\text{min.} \quad [3]$$

a plot of this relation [3] for several GLE detach again two components among the onset population (Figs. 4 in Refs. 51,52, Figs. 3 in 65,66): a 1st peak with $B_0 = 0 - 15$ min. and a 2nd peak with $B_0 > 20$ min after the type-II radioburst maximum, averaged at 8 and 30 min respectively, the last one coinciding with results of 40 MeV scattered component in Delayed-diffusive-type events (implying <u>energy independence of the DC).</u>

- in terms of average times, in general, particles of the PC begin to escape from the corona ~ 20 min. before particles of the DC.
- B_m and B_0 of the Delayed Component are energy-independents.

Method of data analysis (II):

$T_{1/2}$ - anaslysis (width of intensity-time profiles)

- The parameter $T_{1/2}$ (half width of profiles as measured at the level of the maximum intensity) is associated to the time the main bulk of SCR spend in the corona after their acceleration.

- From the 54 registered GLE (1942 - 1992) only 43 have suitable profiles for the analysis.
- Plotting $T_{1/2}$ *vs* heliolongitudeof the associated source to each GLE, one can observe that two distinctive groups are formed (Fig. 2 in Ref. 50, Fig. 5 in 51 & Fig. 1 in 53):
(1) $T_{1/2}$ > 1 hr. : show heliolongitude dependence on the coronal storage time in a V-shaped form, with a minimum near 50° W, close to the foot point of the optimal sun-earth connection (the "garden house" IMF lines) and extending over a broad heliolongitude range, 90° E - 150° W. Such a V-distribution is similar than that found for 20 - 80 MeV protons[68] - the profiles of these events have as a rule a smooth-diffusive shape, with very low anisotropy near the time of maximum intensity.
(2) $T_{1/2}$ < 1 hr : do not show heliolongitude dependence on the coronal storage time - The associated flares occur near the solar limb or behind it (20° - 130° W) in the box zone of the plot, clearly avoiding the optimal heliolongitude cxonnection ~ 50°-70° W.
- their corresponding profiles are of impulsive-like form with sharp rise and rapid decay of intensity, and high degree of anisotropy.
- Events of $T_{1/2}$ > 1 are of the <u>Delayed-Type</u> and those with $T_{1/2}$ < 1 of the <u>Prompt-Type.</u>
- Some of the GLE are "<u>combined-type</u>" (with a DC and a PC in the same event), e.g. the Dec 7, 1982. A liste of Prompt and delayed events according $T_{1/2}$ is given in Tables 1 (Refs. 50, 53) for some events of solar cycles 21 & 22.

It should be mentioned that independent theoretical work support the observational evidences: by numerical solution of the inverse problem of SCR propagation, Miroshnichenko et al[69,70] have reconstructed the ejection time profiles (ETP) and pitch-angle distributions (PAD) for several of the Prompt Component-GLE and turned out to be rather narrows: e.g., in the Feb. 16, 1984 GLE the PAD ia a Gaussian with half-width $\pi/5$, whereas for the "combined" GLE of Feb. 23, 1956 the ETP is an asymetrical curve with half width $T_{1/2}$ ~ 19 min.
- In some GLE as Sept. 29, 1989, time profiles are highly complex, so, that another technique of analysis must be applied to separate the DC and PC.

Method of data analysis (III):
separation of two ejections (peaks) from an undefinited intensity-time profile
- Some GL stations do not present often the anisotropic PROMT COMPONENT (PC) because their acceptance asymptolic cones of particles during the event development are far from the anisotropy axis during the time of the event onset. In such a case a summary (global) intensity profile of the events is constructed by rounding the data of profiles of all stations that have detected the anisotropic PC (Figs. 2 in Ref. 52,55 & Fig. 1 in 57). By substracting from this global curve the observed profile of the station in consideration, it is possible to derive its corresponding PC-profile - That was the case of MIRNY station during the Sep. 29, 1989 GLE : looking to the map of asymptotic directions at ~ 11-12 UT (Fig. 3 in Ref 57), the anisotropy axis passed through the asymptotic cone of the THULE station, whereas the asymptotic cone of MIRNY was directed nearly opposite to the anisotropy vector, so that this station did not "see" the PC at all.

- An estimation of the present author indicates that from the 54 GLE occured in the period 1942-1992, at least 22 of them present a prompt component : - 12 GLE in a well defined form and 10 GLE in superposition with the DELAYED COMPONENT (DL) in which case the separation proceeded as explained before, from one or several of the techniques of analysis previously described. Some of those GLEs (e.g., the june 11 and 15, 1991 events) were particularly notable for long-lasting gamma-ray emission in the high energy range (> 1 GeV): the pure trapping of relativistic particles in the coronal magnetic loops cannot account for the observations. The presence of the second source or two-step ejection would be a possible explanation. However, this possibility requires of special consideration elsewhere

Scenario for SPE with two relativistic components.

Observational data provide evidence that some relativistic SPE (GLE) have two components:

♦ Prompt component that produces a sharp and anisotropic peak.

♦ Delayed component that produces a smooth and isotropic peak.

- these two components cannot be originated near the sun from an isotropic SCR flux and then bifurcated by the so-called "focused" diffusion process, since as noted in work[62] to observe such an important peak "spike-like" as that of the PC, the transport length for particle scattering should be $\Lambda > 1$ AU, so that in order to produce typical ratios between anisotropic PC peak and isotropic DC peaks (>> 1) the SCR flux should be ejected from the sun in a highly anisotropic manner rather than in isotropic manner. Therefore, from the arguments discussed here below, we infer they are originated in two-independent sources:

Source of the prompt component.

The fact that particle ejection of the PC is highly abrupt (coronal storage time $B_m \approx 0$) 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, probably by a secular (deterministic) process and rapidly collimated through the interplanetary magnetic field lines. Such acceleration may occur during magnetic merging in a reconnecting Magnetic Neutral Current Sheet formed between the expanding magnetic bottle and coronal field lines of opposite polarity (e.g. coronal loops or helmet streamers). Schematizations of such an scenario can be appreciated in Fig. 6 of Ref. 51, Figs. 1 & 3 of Ref. 55, Figs. 2 of Refs. 59, 60, Fig. 5 of Ref. 65, Figs 8-10 of Ref. 66. To substantiate in a quantitative form this proposal we have proceded to evaluate the predicted energy spectrum from this kind of acceleration in order to compare with observational ones: to do that, we refer to works[45,46] where a study of the several magnetic neutral current sheet topologies usually associated with the flare phenomenon leads to discriminate among them on basis to their feasibility to reproduce observational spectra. Tables and Figures in works[45,46] show examples of such topologies and the predicted energy spectra, respectively. It is found in those works that the most adequated topology in realistic plasma conditions is that of the model proposed in work[47], and so, it has been adequated[51,59,71] to the neutral current sheet formed in the high corona as previuosly described. The spectrum analytical expression is given in works[45,46], and adapted to the study of prompt events in Eq. 3 of Ref. 51 (or Eq. 1 in Ref. 71): results for several prompt events are shown in Figs. 3 & 3-5 of Refs. 59, 60. It can be appreciated that the spectra predicted from this kind of acceleration describes adequately the observational data.

Source of the delayed component.

The energy-independence of B_0 and B_m for the DC (i.e. particles of all energy have the same coronal storage time before being ejected) and the isotropic behavior at their ejection through a wide heliolongitude extension point out toward - a source connected with a transient, in a closed magnetic structure (usually associated to a Magnetic Bottle) - so, it is proposed that the DC is generated in the flare volume or its vecinity at a height of ~ 0.07 -0.2 $R_\oplus$ and ejected after ~ 30 min from the begining of the acceleration, at a certain height reached after this time with a transient velocity (Bottle or Shock front) of ~ 400 - 500 Km/s. Schematizations can be seen in Fig. 6 of Ref. 51, Figs. 1 & 3 of Ref. 55, Figs. 2 of Refs. 59, 60, Fig. 5 of Ref. 65, Figs 8-10 of Ref. 66. Acceleration of this component is produced by the dissipation of local turbulence to a select number of particles able to undergo resonant interactions with the local turbulent wave modes. For a quantitative substantiation this proposal we have proceded to evaluate the predicted energy spectra from this kind of acceleration in order to compare them with observational ones: to do that we use the analytical expressions derived[19,44] with the aim of describing solar particle spectra through the entire energy domain (including the transrelativistic range), which in the case of Cherenkov (Landau-damping) acceleration by the fast magnetosonic mode is given in equation 2 of Ref. 51 (or Eq. 4 of Ref. 71). Results of the applications to specific solar events are shown in Fig. 7 of Ref. 51 and Fig. 1 of Ref. 71. The fitting of the stochastic acceleration spectrum to observational data is quite good, particularly for the October 22, 1989 event.

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 scenarlo some of the hypothesis must be substantiated. In works[59,60] it was shown that the energy spectra of the prompt component may be satisfactory reproduced assuming impulsiv acceleration in a neutral current sheet. In works[51,71] it was 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 coronas values, respectively. Similarly, the acceleration parameters range within the order of values inferred in other works on basis of the secondary radiation of fiare emissions.

Acknowledgements.

The author as a member of the Grupo Politécnico Mexicano wishes to thank to COFFA of the INSTITUTO POLITECNICO NACIONAL for support in his participation to the 16th ECRS.

References.

1. Lin, R.P., EOS Transactions AGU 75-40, 457 (1994).

2. Chupp, E.L., AIP proc. 374, 3-31 (1995).
3. Reames, D.V., AIP proc. 374, 35-44 (1995).
4. Ramaty, R. and Manndzhavidze, N., AIP proc. 374, 532-544 (1995).
5. Shatzman E., 1966, Les Houches
6. Melrose, D.B., Preprint, 1993.
7. Achterberg, A., Astron. Astrophys. 97, 259 (1981)
8. Kulsrud, R.M. and Ferrari, A., Astrophys. Space Sc. 12, 302-318 (1971).
9. Hall D.E. and Sturrock, P.A., Phys. Fluids 10, 1593, 1967 & 2620 (1967).
10. Stix, T.H., in Waves in Plasmas, Ed.. by AIP (1992).
11. Fisk, L.A., J.G.R. 81. 4633,1(976).
12. Barbosa, D.B., Ap. J. 233, 383 (1979).
13. Miller, J.A., N. Guessoum, and R. Ramaty Ap. J. 361, 701 (1990).
14. Tsytovich, V.N., Soviet Phys USPEKII 2, 370 (1966) .
15. Melrose, D.B., *Instabilities in space and Laboratory plasmas, Cambridge University Press*, (1986).
16. Forman, M. et al., Space Sc. Rev. 18, 341 (1975).
17. Melrose, D.B., Solar Phys. 37, 353 (1974)
18. Ramaty, R. in *Particle Acceleration Mechanisms in Astrophys* AIP Conf. Proc. 56, 135, (1979).
19. Pérez-Peraza, J. and Gallegos-Cruz, A. Ap. J. S. S. 90, 669 (1994); 23rd ICRC 3, 9-12 (1993).
20. Gallegos-Cruz, A. and J. Pérez-Peraza, Ap. J. 446, 400 (1995).
21. Miller, J.A. and D. A. Roberts Ap. J. 452, 912 (1995).
22. Smith, D.F. and J. A. Miller Ap. J. 446, 390 (1995).
23. Miller, J.A. et al. J. G. R. 102, 14631 (1997).
24. Miller,J.A., R. Ramaty and J. Murphy, in Proc. 20 ICRC, 3, 33 (1987).
25. Benz, A. and Smith, D.F., Solar Phys. 107, 299 (1982) ; Lakhina, G.S. and Buti, B., Solar Phys. 165, 329-336 (1996).
26. Miller, J.A. and A. F. Viñas Ap. J. 412, 386 (1993)
27. Tsytovich, V.N., Theory of turbulent Plasma, Consultants Bureau, New York (1977)
28. Melrose, D.B., Plasma Astrophys. Vol. 2, New York, Grodon and Breach (1980).
29. Tsytovich, V.N. et al., Physics Scripta 11, 251-257 (1975).
30. Melrose, D.B. and Kuijpers, J., Ap.J. 323, 338-345 (1987).
31. Lentey, G.T. and Miller, J.A., Ap.J. 493, 451-459 (1998).
32. Gallegos-Cruz, A. and Pérez-Peraza, J., Adv. in Space Res. 13-9, 187-190 (1993).
33. Temerin, M. and Roth, J., Ap.J. 391, L105 (1992); AIP proc. 374, 435-444 (1995).
34. Somov, B.V., AIP proc. 374, 493-497(1995).
35. Somov, B.V. Fundamental of Cosmic electrodynamics, Kluwer Acad. Publ. Dordrecht (1994).
36. Litvinenko, Y.E. and Somov, B.V., Solar Phys.158, 317 (1995).
37. Lampe, M. and Papadopoulos, K. Ap.J. 212, 866 (1977)
38. Heyvaerts, J., in Solar Flare Magnetohydrodynamics, Gordon & Breach Publ. (1981).
39. Miller, J.A. et al., Ap.J. 461, 445-464 (1996).ee
40. Mullan, D.J., Pérez-Peraza, J and Alvarez-M, M., Adv. Space Res. 4, 157-160 (1984).
41. Paper SH-3.1. in the Proc. of the 16th. European Cosmic Ray Simposium, Madrid (1998).
42. Gallegos-Cruz, A. and Pérez-Peraza, J., Ap.J. 446, 400-420 (1995).
43. Schlickeiser, R. , Ap.J.S. 90, 929 (1994).
44. Priest, E.R., in Solar Flare Magnetohydrodynamics, Gordon & Breach Publ. (1981).
45. Pérez-Peraza, J. et al. Proc. 15th. Int. Cosmic Ray Conf. 5, 23-28 (1977).
46. Pérez-Peraza, J. et al., Adv. Space Res. 18, 365-368 (1978).

47. Priest, E.R., Ap.J. 181, 227 (1973).
48. Cliver, E.W., Kahler, S.W., Shea, M.A. and Smart, D.F., Ap.J. 260-1, 362 (1982).
49. Heristchi, Dj., Trottet, G. and Pérez-Peraza, J., Solar Phys. 49, 151-175 (1976); Pérez-Peraza, J., J.G.R. 80, 3535-3542 (1975).
50. Vashenyuk, E.V., Miroshnichenko, L.I., Sorokin, M.O., Pérez-Peraza, J. and Gallegos, A. Adv. Space Res. 14-10, 711-716, 1994.
51. Miroshnichenko, L.I., Pérez-Peraza, J., Vashenyuk, E.V., Rodríguez-Frías, M.D., Del Peral, L. and Gallegos-Cruz, A., in High Energy Solar Physics, AIP Proc. 374, 140-149 (1996).
52. Miroshnichenko, L.I., Pérez-Peraza,J., Vashenyuk, E.V., Rodríguez-Frías, M.D., Del Peral, L. and Gallegos-Cruz, A., 24Th ICRC 4, 34-37 (1995).
53. Vashenyuk, E.V., Miroshnichenko, L.I., Sorokin, M.O., Pérez-Peraza, J. and Gallegos-Cruz, A., Geomag. and Aeron. 33-5, 569-575 (1994).
54. Vashenyuk, E.V., Fischer, S. and Gvozdevsky, B.B., 23rd ICRC 3, 266-269 (1993).
55. Miroshnichenko, L.I., J. Moscow Phys. Soc. 7, 17-30 (1997).
56. Vashenyuk, E.V., Fischer, S., Vandas, M., Shea, M.A., Smart, D.F., 24th ICRC 4, 317-320 (1995).
57. Vashenyuk, E.V., Miroshnichenko, L.I., Pérez-Peraza, J., Kanamen, H., tanskanen, P. 25th ICRC 1, 161-164 (1997).
58. Pfotzer, G. Nuovo Cimento (Supp) 8-10, 180 (1958).
59. Pérez-Peraza, J., Gallegos, A., Vashenyuk, E.V., Miroshnichenko, L.I., Geom. and Aeron. 32-2, 159-167 (1992).
60. Pérez-Peraza, J., Gallegos, A., Vashenyuk, E.V., Miroshnichenko, L.I, 22nd ICRC 3, 5-8 (1991).
61. Cramp, J., Duldig, M.L. and Humble, J.E., 23rd ICRC, 3, 47-54 (1993).
62. Earl, J.A., Ap.J. 206, 301 (1976).
63. Duggal, S.P., Guidi, Y, and Pomerantz, M.A. Solar Phys. 19, 234 (1971);
64. Duggal, S.P., Rev. Geophys. Space Phys. 24, 204 (1979).
65. Miroshnichenko, L.I., Pérez-Peraza, J., Alvarez-M, M., Sorokin, O.M., Vashenuyk, E.V. and Gallegos, A., 21st ICRC 5, 5-8 (1990).
66. Vashenyuk, E.V., Miroshnichenko, L.I., Sorokin, M.O., Pérez-Peraza, J., Alvarez-M., M. and Gallegos, A., Preprint PGI 90-01-70, Academy of Sciences of USSR (1990).
67. Reinhard, R. and Wibberenz, G., Proc. 17th ICRC, 2, 1372, (1973).
68. Van Hollebeke , M.A.I., Sung, L.S. and McDonald, F.B., Solar Phys. 41, 189, (1975).
69. Miroshnichenko, L.I., and Sorokin, M.O., Geom. and Aeron., 27, 893, 1987 & 29, 309 (1989); 20th ICRC 3, 117-120 (1987).
70. Miroshnichenko, L.I., Sorokin, M.O. and De Koning, C.A., 25th ICRC 1, 165-168 (1995).
71. Miroshnichenko, L.I., Pérez-Peraza,J., Vashenyuk, E.V., Rodríguez-Frías, M.D., Del Peral, L. and Gallegos-Cruz, A., 24Th ICRC 4, 38-41 (1995).