THE PRIMARY SPECTRUM OF SUPRATHERMAL SOLAR PARTICLES

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ABSTRACT

Assuming that the primary production of non-relativistic flare particles occurs in solar topologies such as neutral current sheets and magnetic flux loops, we derive acceleration spectra of particles accelerated within these kind of magnetic configurations. A general spectral shape of the form $N(E)=A(E/E_0)^{-\gamma_1} \exp(-\gamma_2 (E/E_0)^{\gamma_3})$ (with A, E_0, γ_1, γ_2 and γ_3 defined by each model) is obtained in the case of neutral current layers. Among the magnetic flux loop topologies, current interruption models furnish an inverse power law spectrum in kinetic energy. The best description of solar particles spectra, among the several alternatives analized through this work is obtained from the neutral sheet configuration of PRIEST.

INTRODUCTION

At present it is widely spread the concept that solar particles in prompt events are generated in two main acceleration steps: an impulsive process narrowly associated with the local instability that triggers the flare process itself, followed occasionally by a slower process, probably of stochastic character which eventually rises particles up to relativistic energies. By studying the energy spectrum of the low energy component in prompt events, (which presumptively have not gone through secondary acceleration) we claim to search for the adequate topology of flare regions, and thus, to discriminate among the several existing hypothetical assumptions on flare theories, in order to delineate more realistic models. Therefore we have developed analytical expressions for the primary spectrum of flare particles from inherent features of each solar flare model (Ref. 1). However it is clear that similar assumptions may be developed at other astrophysical scales, as can be the case of an impulsive acceleration process in interplanetary neutral current sheets associated for example to LESP events (the so called shock spike increases). Concerning flare models, two main categories can be distinguished according to the magnetic field configuration (e.g. (Ref. 2), (Ref. 3)): (a) neutral current sheets and (b) magnetic flux tubes. We have limited our analysis to those flare models where the impulsive electromagnetic field or the magnetic field configuration are explicitly given. We have shown on Table 1 the field topologies of the selected current sheet models.

THE IMPULSIVE ACCELERATION SPECTRUM

In order to obtain the energy spectrum of particles accelerated in these kind of configurations we have considered that as the accelerating force proceeds from a Coulombian force field, hence the final energy distribution of particles depends on the random initial positions within the acceleration region, such that the differential energy spectrum by unit time and unit length may be expressed as follows (Ref. 4)

$$N(E)dEdZ = J_0 |dX_0/dE| dEdZ \qquad (1)$$

where J_0 is the local flux flowing at the boundary of the acceleration region and X_0 is the initial particle position. From Eq. (1) it follows that in order to establish the modulating factor $|dX_0/dE|$ of the flux J_0 it is necessary to study the behavior of particles in the electromagnetic field inherent to each model.

Neutral Current Sheets

The procedure to obtain $|dX_0/dE|$ in this case, is basically based on the establishment of particle trajectories within configurations of Table 1. By solving the motion equations in terms of modified Bessel functions we obtain (Ref. 1) the initial position of particles as a function of their energy

$$X_0 = 1.36\,\delta \exp\left[-1.12(E/E_0)^{3/4}\right] \qquad (2)$$

where δ is the diffusion region width in the neutral layer and E_0 is a characteristic energy which value depends on inherent features of each model. By taking the derivate of Eq. (2) and introducing it in Eq. (1) a general expressions for the differential energy spectrum of particles accelerated in neutral current sheets is obtained

$$N(E)dEdZ \simeq A(E/E_0)^{-1/4} \exp\left[-1.12(E/E_0)^{3/4}\right] dEdZ \;(cm^{-1}s^{-1}eV^{-1}) \qquad (3)$$

Sweet (1958) Parker (1963)	$B = (0, \frac{X}{\delta}B_0, 0)$
Petschek (1964) Friedman (1969)	$B_I = (2M_0B_0, B_0, 0)$ $B_{II} = (M_0B_0, 0, 0)$ $B_{III} = (-3M_0B_0, B_0, 0)$ $B_{IV} = (-M_0B_0(1+X/\delta), (-X/\delta)B_0, 0)$ $B_V = (-M_0B_0(2+X/\delta), (-X/\delta)B_0, 0)$
Syrovatsky (1966, 1974)	$B = B_0(-Y, X, 0)$
Coppi-Friedland (1971)	$B = [(va_j/c_s\delta)B_0, (v(1+a_j)/c_s\sigma)B_0, 0]$ $a_j = 1$, c_s = sound velocity
Yeh-Axford (1970)	$B = (-\epsilon\mathcal{E}^2/2c^2)[(1+1/\cos 2\beta)Y, (-1+1/\cos 2\beta)X, 0]$ $\beta = 65°$
Sonnerup (1970)	$B_x = B_1[6.7(Y/\ell) + c_3(Y/\ell)^3 + c_5(Y/\ell)^5]$ $B_y = B_1[6.7(X/\ell) + b_3(X/\ell)^3 + b_5(X/\ell)^5]$ $\ell = (1+(2)^{1/2}V\delta/v)$; c_3, c_5, b_3 and b_5 = constants
Priest (1973)	$B = [(2B_1/L)Y, (B_0/L)X, 0]$
Smith-Raadu (1972)	$B = [B_0, -(B_0/L)X, 0]$
Priest-Raadu 1975	$B = (0, B_0(t)\,\mathrm{sen}[\pi X/2\delta(t)], 0)$ $B_0(t) = cte\ \delta(t)^{-1/l}$ $1 \le l \le 2$

Table 1. Magnetic field configurations of different models, B_0 = input mag. field strength into the diffusion region, B_1 = emergent field after reconnection, δ = half-width, L = length of the sheet, $M_0 = v/V$, v and V the diffusion and Alfvén velocities, $\mathcal{E}$ = induced electric field

where $A = Kn v\,\delta/E_0$, with $K = (\pi^{1/2}e^{\pi/12})/\Gamma(2/3)2^{1/4}\,3^{1/6} = 1.1436$. It can be noted that the current density $J_0 = nv$ depends on each model through the incoming diffusion velocity and on the compressibility or incompressibility of the medium concentration. In the case of the Petschek's model the spectral shape is not exactly described by Eq. (3), because the predominance of fluctuating electric fields over the constant field, induced by the diffusion of lines, in two regions of the configuration (Ref. 1). It follows from Eq. (3) that the evaluation of differential energy spectra of particles accelerated in neutral current sheets require the characteristic values δ, v and E_0 that we have respectively summarized through Table 2 to 4 for both, the incompressible and compressible cases, and for a typical set of flare parameters: $n = 10^{11}\ cm^{-3}$, $B_0 = 500$ gauss, $\sigma = 10^{13}s^{-1}$, $L = 10^9$ cm and $T_e = 10^5\ °K$. From the examination of Table 4, it can be seen that with the exception of the Priest and Yeh-Axford configurations (Ref. 5 and 6 respectively) the other models are not able to describe solar particle spectra, because of the abrupt fall in intensity at very low energies whatever the flare parameters between the following values: $n = 10^9 - 10^{13}$ cm^{-3}, B= 100 - 500 gauss, $T_e = 10^5 - 10^7$ °K, $L = 10^7 - 10^9$ cm and $\sigma = 10^{13} - 10^{17}$ s^{-1}. On Fig. 1 we have plotted for the Priest and Yeh-Axford models, the energy spectra according to the several sets of parameters shown in Table 5, where we have included the maximum energy achieved by particles in each model $E_{max} = eEL = (e/c)vBL$. It can be appreciated that according to the restrictions imposed by the observational value of E_{max} (<20 GeV) (Ref. 7), the best description of a solar particle spectrum is that obtained with the Priest IV ($n > 10^{12}$ cm^{-3}), unless the sheet length L were taken two orders of magnitude lower.

Magnetic Flux Tubes

Among the magnetic flux loop models we have analysed only those where the impulsive electromagnetic field is explicitly given, disregarding hence, models where acceleration is performed by fluctuating electric fields. One of the most popular concepts in flux loop models is electric disruption in the solar atmosphere as for instance the model proposed by Carlqvist and Alfvén (Ref. 8).

Diffusion Region Width ℓ (cm)

Models	Incompressible	Compressible
Sweet – Parker	$(c/0.87)(L/4\pi\sigma V)^{1/2} = 5.2 \times 10^{[illegible]}$	$(cLB_0)[n_0/\sigma L(3mkT_e)^{1/2}]^{1/4} = 5.4 \times 10^{[illegible]}$
Petschek	$c^2/0.4\pi V\sigma = 0.207$; $\alpha = 0.2$	$(1+\alpha)c^2/0.8\pi\sigma V = 0.124$; $\alpha = 0.2$
Syrovatsky		$4\pi M n_0 / B_0^2 (3kT_e/M)(1+T_i/T_e) = 0.383$
Coppi - Friedland		Arbitrary value: 100
Yeh – Axford	$c^2/2.41V\sigma = 0.107$	
Sonnerup	$\times(1/eB_0)(mkT_e/3)^{1/2} = 8.9 \times 10^{[illegible]}$	
Priest	$c^2/0.715\sigma V = 0.363$	
Smith – Roadu	Arbitrary value: 1	
Priest – Roadu	Arbitrary value: 1	

Table 2 The spectrum parameters for incompressible and compressible flare models: $V = B_0/(4\pi n_0 m)^{1/2}$ is the Alfvén velocity; m and M are the proton and electron mass respectively. T_i and T_e are the ionic and electronic temperatures respectively ($T_i/T_e = 0.1$); k is the Boltzmann constant.

Diffusion Velocity of Field Lines V (cm^{-1})

Models	Incompressible	Compressible
Sweet – Parker	$(c/0.87)(V/4\pi\sigma L)^{1/2} = 1.8 \times 10^{[illegible]}$	$[(B_0^2/48\pi^2 n_0 \sigma L)(3/mkT_e)^{1/2}]c^{1/2} = 1.3 \times 10^{[illegible]}$
Petschek	$0.1V = 3.45 \times 10^{[illegible]}$	$0.2V/(1+\alpha) = 5.75 \times 10^{[illegible]}$
Syrovatsky		$\frac{B_0^4 c^2}{16\pi^3 m\sigma n_0 (3kT_e/M)(1+T_i/T_e)} = 1.8 \times 10^{[illegible]}$
Coppi - Friedland		Arbitrary value: $10^{[illegible]}$
Yeh – Axford	$2.41V = 8.34 \times 10^{[illegible]}$	
Sonnerup	$0.059V = 2.03 \times 10^{[illegible]}$	
Priest	$0.057V = 1.96 \times 10^{[illegible]}$	
Smith – Roadu	Arbitrary value: $10^{[illegible]}$	
Priest – Roadu	Arbitrary value: $10^{[illegible]}$	

Table 3 The spectrum parameters for incompressible and compressible flare models: $V = B_0/(4\pi n_0 m)^{1/2}$ is the Alfvén velocity; m and M are the proton and electron mass respectively. T_i and T_e are the ionic and electronic temperatures respectively ($T_i/T_e = 0.1$); k is the Boltzmann constant.

Spectral Characteristic Energy E_0 (eV)

Models	Incompressible	Compressible
Sweet – Parker	$[(eB_0c^2/(0.87)^2 4\pi\sigma)(V/4\pi\sigma L)^{1/2}]m^{1/3} = 0.19$	[illegible] $= 0.08$
Petschek	$(0.1eB_0cV/4\pi\sigma)^{2/3} m^{1/3} = 116.9$	$(0.2ecB_0V/4\pi(1+\alpha)\sigma)^{2/3} m^{1/3} = 164.4$
Syrovatsky		$\{ecB_0^3 M/16\pi^3 m\sigma n_0 3kT_e(1+T_i/T_e)\}^{2/3} m^{1/3} = 77.3$
Coppi - Friedland		$(e^2 vB_0 c/4\pi G_c)^{2/3} m^{1/3} = 31.36$; $G_c = 10^{[illegible]}$
Yeh – Axford	$\{4.82ec^2B_0/4\pi\sigma[(1/\cos 2\theta)-1]\}^{2/3} m^{1/3} = 8.01 \times 10^{[illegible]}$	
Sonnerup	$(2.41VeB_0c/4\pi\sigma c_0)^{2/3} m^{1/3} = 3.0 \times 10^{[illegible]}$; $c_0 = 67$	
Priest	$(3.25 \times 10^{[illegible]} eLB_0V^2/2c)^{2/3} m^{1/3} = 994 \times 10^{[illegible]}$	
Smith – Roadu	$(4ev^2B_0/c)^{2/3} m^{1/3} = 1.37 \times 10^{[illegible]}$	
Priest – Roadu	$(2eB_0v^2 e^{[illegible]}/cte. \pi c)^{2/3} m^{1/3} = 6.41 \times 10^{[illegible]}$; $f = 1.5$	

Table 4 The spectrum parameters for incompressible and compressible flare models: $V = B_0/(4\pi n_0 m)^{1/2}$ is the Alfvén velocity; m and M are the proton and electron mass respectively. T_i and T_e are the ionic and electronic temperatures respectively ($T_i/T_e = 0.1$); k is the Boltzmann constant.
* The constant has been arbitrary chosen as unit

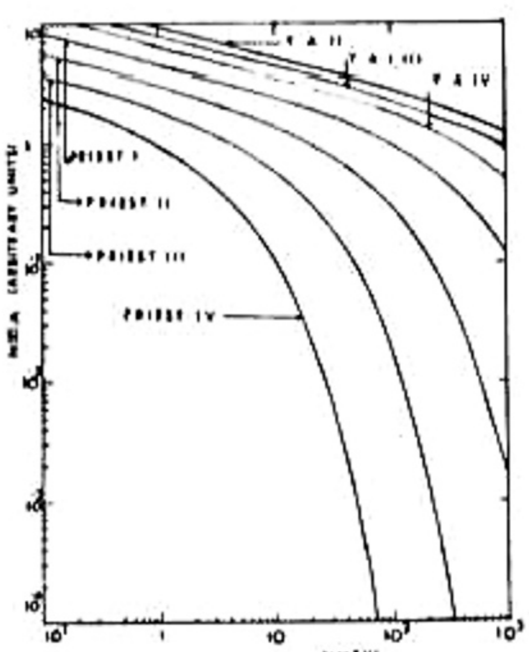

Fig. 1 The Priest and Yeh-Axford spectra

Developing again some calculations we arrive to the following spectral shape

$$N(E)dEdZ = AE^{-1/2}dEdZ \ (\text{cm}^{-1}\text{s}^{-1}\text{eV}^{-1}) \quad (4)$$

with a high energy cutoff given by $E_{max} = 3.74\times10^2 n$ (eV) therefore according to this model, non-relativistic particles should be generated in a region of $n \leqslant 10^7 cm^{-3}$. Other interruption circuit models also predict inverse power law spectra, but they do not seem to be able to explain solar particles spectra in prompt events, because the predicted energy cutoff is extremely low, as for instance the Takakura model (Ref. 9) where $E_{max} < 5$ MeV or the Kaburaki model (Ref. 10) where $E_{max} < 15$ KeV.

CONCLUSIONS

We have derived energy spectra from an impulsive acceleration process in neutral current sheets, which have a similar shape to that obtained from an stochastic process, in the same kind of configurations, by solving a Fokker Planck equation (Ref. 11), and which general form may be expressed as $N(E) \sim (E/E_0)^{-\gamma_1} \exp(-\gamma_2 (E/E_0)^{\gamma_3})$. Among the several neutral current sheet configurations analysed, the Priest model seems to be the more adequated to describe low and high energy particle spectra at both the coronal and cromospheric levels, whereas the Yeh-Axford configuration is rather adequated to explain energy spectra of solar relativistic particles, provided $n \geqslant 10^{13} cm^{-3}$ and the current sheet dimensions $\leqslant 10^7$cm. Because the scarcity of Multi-GeV events we prefer the picture of primary acceleration at coronal levels, and therefore a source of the Priest type configuration, such that occasionally when the appropriate condition exists, particles may be reaccelerated at chromospheric levels, probably, by an stochastic process.

		I	II	III	IV
	n (cm^{-3})	10^{11}	10^{11}	10^{11}	10^{11}
Yeh-Axford (1970)	δ (cm)	3.4×10^{-3}	0.107	0.341	1.07
	v ($cm\ s^{-1}$)	2.6×10^{9}	8.3×10^{8}	2.6×10^{8}	8.3×10^{7}
	E_0 (MeV)	3.7×10^{4}	8.0×10^{3}	3.7×10^{3}	1.7×10^{3}
	A $(cm\ s\ eV)^{-1}$	2.7×10^{7}	1.28×10^{9}	2.7×10^{11}	5.9×10^{11}
	E_{max}	1.3×10^{6}	4.0×10^{4}	1.3×10^{3}	417.0
PRIEST (1973)	δ (cm)	1.1×10^{-2}	0.363	1.15	3.63
	v ($cm\ s^{-1}$)	6.2×10^{7}	1.9×10^{7}	6.2×10^{6}	1.9×10^{6}
	E_0 (MeV)	461.0	99.4	21.4	4.6
	A $(cm\ s\ eV)^{-1}$	1.5×10^{7}	8.2×10^{9}	4.7×10^{11}	1.7×10^{13}
	E_{max} (GeV)	311	98	31	9.8

Table 5. The Priest and Yeh-Axford spectra parameters for B=500 gauss; $L=10^9$ cm, $\sigma=10^{11} s^{-1}$. Set I is given with $\sigma=10^{14} s^{-1}$.

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