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CORONAL TRANSPORT OF SOLAR FLARE PARTICLES

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RESUMEN

Se desarrolla una descripción cuantitativa de la propagación azimutal de partículas aceleradas en ráfagas solares. Se resuelven las ecuaciones de transporte coronal dentro del marco de un modelo de dos etapas de propagación. Se propone un escenario acorde a la descripción cuantitativa.

ABSTRACT

We develop a quantitative description of the azimuthal propagation of solar flare particles. The transport equations are solved within the frame of a two-step model. A scenario for the global phenomenon is proposed.

Key words: SUN-CORONA – SUN-FLARES – SUN-MAGNETIC FIELDS

I. INTRODUCTION

It is widely accepted that solar flare particles undergo azimuthal propagation through the solar corona before reaching the interplanetary magnetic field. The following observational features constitute the general requirements for a coronal propagation model:

1) The onset time of the event and the time of maximum intensity increase with the angular separation between the observer and the flare location.

2) The azimuthal distribution of flare particles tends towards uniformity for large times during the decay phase of events.

3) A widening of the time-intensity profile occurs when the angular distance increases from the flare site to the observer.

4) In superposition with feature (2) the point of maximum intensity moves in heliolongitude out of the flare site.

5) The existence of a fast process around the flare site, covering a region of about $60°$-$100°$ of extension in one hour approximately. Outside this Fast Propagation Region (FPR), transport is performed at a rate of ($24°$-$93°$)-day^{-1}.

6) Longitudinal transport of low energy particles is independent of particle energy and practically independent of particle rigidity. However, a weak statistical dependence on particle velocity has been found of the type $t\psi \sim v^{-0.5} \cdot R^{-0.07}$; where t_ψ is the traveling time over a certain angular distance ψ, and v and R are the velocity and rigidity of the particles, respectively. The azimuthal propagation of high energy solar particles tends to behave in an energy-dependent manner.

7) The spectral index of the power law energy spectra ($I \sim E^{-\phi}$) behaves in the following manner: it increases with angular distance from the flare, during the early phases of some events, while in others, ϕ remains practically constant; but it may decrease with angular distance during the decay phase of some events.

8) The propagation of solar flare particles is controlled to a certain extent, by the photospheric magnetic field sectors. Particle fluxes crossing a sector boundary between two sectors of opposite polarity are strongly modified: the observed particle flux is greatly decreased while the times of onset and peak intensity are increased.

II. TRANSPORT EQUATIONS FOR CORONAL PROPAGATION

According to properties (1) to (3) the coronal azimuthal propagation shows the typical behaviour of diffusive transport. If azimuthal transport were exclusively accomplished by diffusion, the traveling time should present a velocity dependence of the form $t_\psi \sim 1/v$. In addition, according to property (4) a longitudinal drift of the particle flux may be inferred to reproduce the coherent shift of the flux peak (Reinhard and Wibberenz 1974). Following Mullan and Schatten (1972) for a suitable coronal magnetic field, particles drift across the field lines at a rate $\sim v^2/(1 - v^2)^{0.5}$. This is translated into a velocity-dependent propagation of the form $t_\psi \sim v^{-p}$, ($p \geqslant 2$). Therefore the velocity dependence related to properties (1) to (4) is of the form

$$t_\psi = t_{diff} + t_d \cong v^{-1} + v^{-p} \sim 1/v \ .$$

However, according to property (6) the velocity dependence during azimuthal coronal transport is of the form $t_\psi \sim v^{-0.55}$.

From these facts, it can be argued that the velocity dependence appears from the combination of the mentioned processes, with a velocity independent propagation taking place in a different region, such that the resultant velocity is of the form

$$t_\psi \sim 1/v + \text{const.} \sim v^{-q} \, (0 < q < 1) \quad .$$

Since the diffusive feature of azimuthal propagation increases for larger distances to the source, and the shift of the peak intensity may reach up to 100° from the flare, we assume that the velocity-dependent transport occurs outside of the FPR. On the other hand, property (5) suggests that within the FPR the transport processes are different from those in the outer region. Hence, instead of the static magnetic field background where propagation tends to be energy dependent, the dynamical character of coronal magnetic fields is required in association with the FPR. In this region a convection-like process in which all particles propagate coherently at a definite velocity, V_c may be assumed: Denoting by N(**r**,t) the number density of particles at point **r** and time t, with coordinate origin at the center of the sun, the equation which gives the evolution of N(**r**,t) within the FPR appears from the condition of particle conservation,

$$\frac{\partial N}{\partial t} = - \frac{V_c}{r_a} \frac{\partial N}{\partial \psi} \quad . \tag{1}$$

Although the propagation takes place isotropically from the flare, only longitudinal effects can be detected. Particle transport is accomplished in this way through a layer concentric with the sun, of radius r_a. A solution of (1) that gives a coherent pulse of particles propagating in the azimuthal direction is,

$$N(\psi, t) = \frac{N_a}{4\pi \, r_a^{-3} \, (1 - \cos \psi_0)} \times \delta\left(\frac{r_a}{V_c} (\psi - \psi') - t\right) \tag{2}$$

where ψ' is the position of the flare, N_a the number of accelerated particles, and ψ_0 the extension of the FPR. The convected flux distributes itself uniformly all over the top of the FPR extension, so that the initial condition for propagation outside the FPR is

$$N(\psi, 0) = \begin{cases} \dfrac{N_a}{4\pi \, r_a^{3} \, (1 - \cos \psi_0)} & |\psi| \leqslant \psi_0/2 \\ 0 & \psi_0/2 < |\psi| \leqslant \pi \, . \end{cases} \tag{3}$$

Once particles abandon the FPR volume, they are conveyed by diffusion and drift and are lost into the interplanetary space (Reinhard and Roelof 1973). The corresponding transport equation is

$$\frac{\partial N}{\partial t} = \frac{1}{r_b^2 \, \text{sen} \, \psi} \frac{\partial}{\partial \psi} \left(K_\psi \, \text{sen} \, \psi \, \frac{\partial N}{\partial \psi}\right) - \frac{V_d}{r_b} \frac{\partial N}{\partial \psi} - \gamma N \, , \tag{4}$$

where K_ψ is the azimuthal diffusion coefficient, V_d the drift velocity, γ the escape rate and r_b the radial distance from the center of the Sun, at which azimuthal transport takes place. Equation (4) with the initial condition given in equation (3) has been solved numerically by the Crank-Nicolson method. It can be appreciated from equation (3) that the results do not depend on V_c. It must be emphasized that although equation (4), as stated, also applies to the heliolongitudes associated with the top of the FPR, the difference with equation (1) is that they operate at different heights in the corona (r_a and r_b respectively), and at different times. The values of the parameters K_ψ, r_b, V_d and γ that appear in equation (4) were in accordance with previous studies of coronal propagation and have been varied over a reasonable range. For the height r_b we assumed 1.8 $R_\odot$ from the center of the Sun. Concerning the escape rate, this might, in principle, be a function of position, ψ, and of the energy, rigidity or velocity of the particles. However we considered it as constant. We used $\gamma = 36000 \text{ s}^{-1}$ according to Ng and Gleeson (1976), and $\gamma = 3600 \text{ s}^{-1}$ according to Reid (1964). Nevertheless the results obtained with both values of γ were essentially the same. This proves that the model is weakly sensitive to variations in the loss rate. The results displayed in Figures 1 to 3 are independent of the parameters N_a and r_a, because they are given in terms of $N_0 = N_a/4\pi r_a^3$.

In Figure 1 we show the angular distribution of particles at different times after leaving the FPR: a dimension $\psi_0 = 100°$ for the FPR was considered, and the diffusion coefficient, K_ψ and drift velocity, V_a, were taken as typical of $\sim$ 100 MeV protons. An interesting effect can be observed in this figure. In the direction of the assumed drift velocity around $\psi = 5°$, the particle density increases over the initial value and later this maximum is shifted to longer longitudes as expected by property (4). This accumulation of particles is the result of the higher efficiency of the drift rate ($V_d \sim v^p$) over the diffusion rate ($V_{diff} \sim v$), that is, azimuthal diffusion from the right to the left, in the side of positive longitudes, is "delayed" together with an "acceleration" of the transport from left to right, in the left side of the flare, due to the effect of the drift. The reason for the anomalous accumulation to initiate near the flare site is associated to the fact that, at t = 0 the distribution through $\psi_0 = 100°$ is uniform, such that if there was drift but only diffusion, a "center of equilibrium" could be considered at $\psi = 0°$. However, because the drift starts simultaneously to the diffusion, the initial concentration is precisely near the "center of equilibrium" with a slight shift toward the direction of the drift (at $\sim \psi = 5°$). As time elapses the peak moves toward larger positive heliolongitudes, at a speed which depends on the relative rate between drift and diffusion. In agreement with property (2) we see in this figure a certain trend for azimuthal dispersion of particle fluxes with time. At $t \sim 0$, there is no particle flux outside of $\psi = \pm 50°$, and as time elapses particles near +50° are either pulled by diffusion to lower longitudes, or pushed to $\psi > +50°$ by drift and diffusion, but no particles may be pulled by diffusion from $\psi > +50°$ to $\psi < +50°$. Similarly, near −50°, particles are either pulled toward the flare direction by drift and diffusion, or pushed out to the left by diffusion. Those particles pushed out of ±50° are found at later times, t = 108 s, at larger heliolongitudes, and so on, progressively.

In Figure 1 it can also be appreciated that, for relatively long times, a sharp decrease in intensity remains near the flare site, as the peak is drifting in azimuth. This is again a remanent effect of particle dispersion out of ±50°, and particle accumulation in the sense of the drift. In the right side sector, diffusion is preferentially toward large positive longitudes, very few particles diffuse toward low longitudes because of the counter-effect of the fast drift, avoiding a normal dispersion toward central longitudes. On the other hand, on the left side sector, diffusion toward central longitudes is accelerated by the superposition of the drift, pushing particles to the moving peak longitude and avoiding again a normal dispersion near the initial point of equilibrium.

Figure 2 shows the time-intensity profile at the level of the solar corona for three different heliolongitudes: (a) the anomalous point, at about 5° from the flare, (b) at a point above the FPR (within $\psi_0 = 100°$) other than the anomalous point, (c) at a point outside the FPR extension. As it might be expected the profile in (c) is typical of a diffusive process, and the maximum is shifted relative to that of (a) and (b), as expected by property (1). In agreement with feature (3) the widening of profile with angular distance can be appreciated in Figure 2.

The results obtained until now represent particle distributions in the upper corona, which apply to particles reaching the base of the interplanetary field lines, but not the observed fluxes. To reproduce the observational fluxes at the orbit of the earth we must incorporate interplanetary propagation effects. Since interplanetary transport is along field lines, the heliolongitudinal distribution at the escape from the corona will not be modified; thus we are only concerned with the behaviour of the flux time-intensity profiles. To do so, we have employed the simpler description of interplanetary transport; i.e., diffusion along magnetic flux tubes with a constant diffusion coefficient K. Particles that are impulsively ejected from the Sun

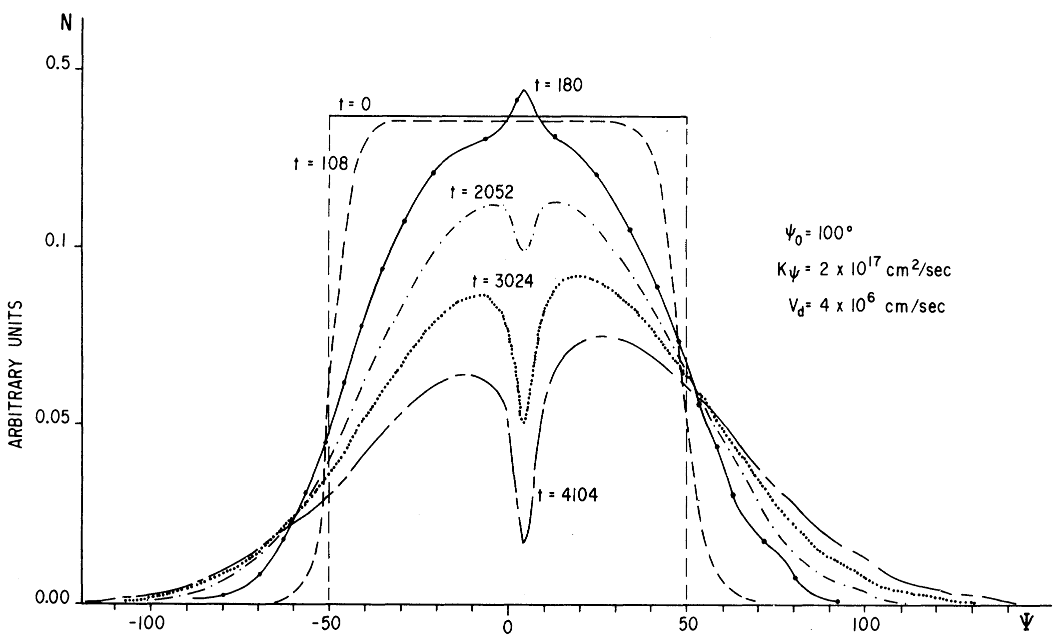

Fig. 1. Angular distribution of particles, t is time after escape from the FPR.

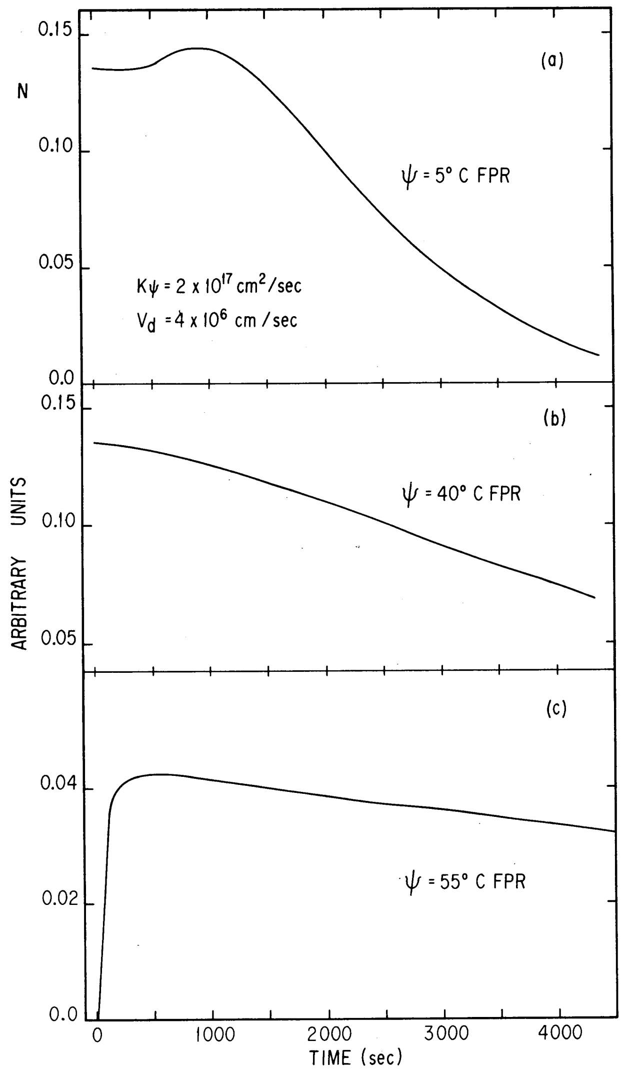

Fig. 2. Time intensity profile for three different longitudes.

distribute in the interplanetary space in the following form (Parker 1963)

$$U(\mathbf{r}, t) = \frac{N}{(4\pi k t)^{3/2}} \exp(-r^2/4 k t) , \qquad (5)$$

where **r** is the distance from the upper corona along a field line and N the number of ejected particles when ejection is not impulsive but gradual, the observed time profile is obtained from the convolution of equation (5) with the injection profile given by equation (4) as $\gamma N(\psi, t)$. If we denote by $W(r,\psi,t)$ the observed particle fluxes, we have

$$W(\mathbf{r},\psi, t) = \int_0^t \gamma N(\psi, t-\tau) \, U(\vec{\mathbf{r}}, \tau) \, dt , \qquad (6)$$

where τ is the interplanetary travel time and $t-\tau$, the travel time in the corona.

Figures 3 and 4 show W for the flux N as given in Figure 2*c* and 2*a* respectively. We can appreciate that the shape of the coronal time profile is lost. However, the shift of the event onset and of the peak intensity to larger times with the increase of angular distance is conserved, as well as the broadening of the profile, as stated in properties (1) and (3). For comparison we have also computed the interplanetary profile associated with impulsive ejection, equation (5), to illustrate the delay of the onset time and the time of peak intensity when a coronal propagation with gradual ejection is considered. Similar results are obtained for low energy particles, but with a delay in the time scales of the phenomenon.

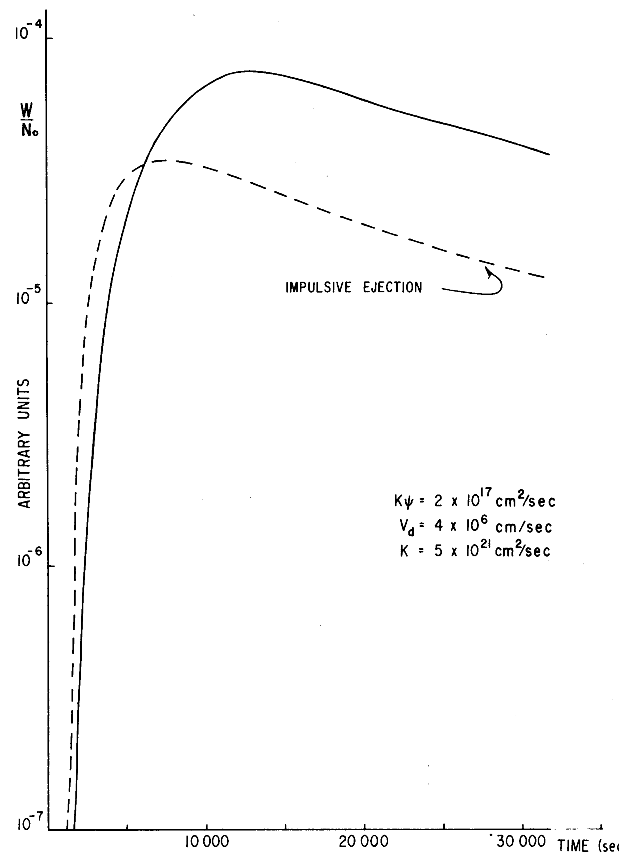

Fig. 3. Observed particle flux for $\psi = 55°$.

III. SCENARIO FOR CORONAL PROPAGATION

The bulk of flare accelerated particles are distributed in longitude before escaping. Azimuthal distribution takes place in two different stages: the first one is attributed to convective transport produced by flare phenomena, such as the plasma expansion associated to

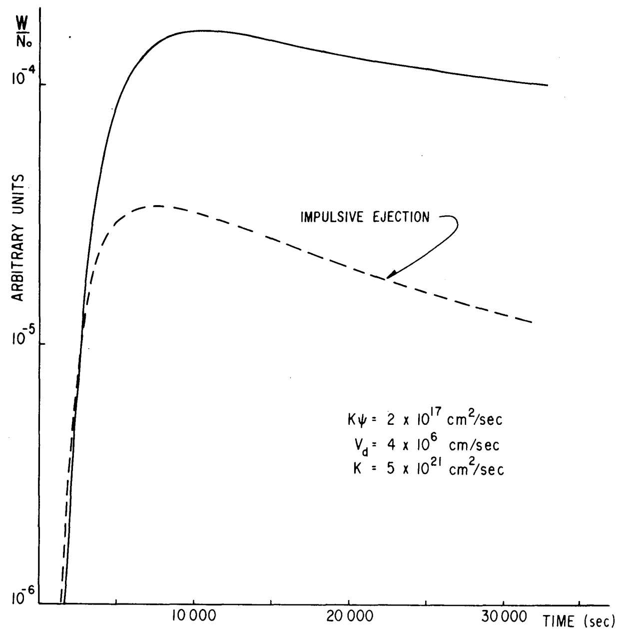

Fig. 4. Observed particle flux for $\psi = 5°$.

the flare blast wave (Palmer and Smerd 1972), or an expanding magnetic bottle associated with closed magnetic loops near the flare site (Schatten and Mullan 1977). Under conditions of high temperature a dynamical behavior of the magnetic field lines is established which is related to the high plasma conductivity. The accelerated particles remain practically constrained behind the shock, or within the bottle, until the end of the dynamical behavior of the field lines, due to defreezing of the field lines and the plasma, or to some kind of instability subsequent to the cooling of the expanding plasma. Meanwhile, the net transport of particles is that of the expanding region, with a relatively high velocity of 250-400 km s^{-1}.

Once convection is stopped, particles fill the top of the FPR, and the second stage of propagation is carried out by drifts and diffusion, as particles escape through open field lines. Since transport is at the coronal level, the basic motion is along the north-south field lines of the general magnetic field of the Sun. Diffusion may take place in the background of coronal irregularities, or by means of hydromagnetic waves. However, in order to assure mass independence with linear velocity dependence for the scattering process, diffusion should be accomplished by static scattering centers, as for instance, in association with ephemeral active centers. Particle drift along the north-south field lines is produced in the azimuthal direction.

The diffusing and drifting particles reach open field lines and escape into the interplanetary space: because these processes are velocity-dependent, as discussed in the previous section, the escape rate $\sim v^s$, may vary from a slight dependence $(0 < s < 1)$ to a strong dependence $(s > 2)$. Such as suggested by point 7(a), in the early phase of the event, these effects are translated into a nearly constant behaviour of the spectral index ϕ with angular distance (when $0 < s < 1$), to a strong dependence of ϕ with angular distance (when $s < 2$); in this case the more energetic particles may escape earlier. In the decay phase of the event, the decrease of ϕ, as suggested by 7(b), is associated with the effect on the escape rate of the drift of the peak intensity to far longitudes, and the uniformity of fluxes through all longitudes.

Propagation is not completely uniform through all the solar disk, but the diffusion coefficient and drift velocity direction are modified when particles find a region of opposite magnetic polarity. In fact, according to the description of Svalgard *et al.* (1974) of the coronal magnetic field structure over sector boundaries, there is a neutral current sheet lying along the sector boundary. Therefore, particle fluxes reaching a sector boundary are modified due to the drift along the neutral sheet by a similar process to that suggested by Fisk and Schatten (1972).

Finally, the effect of interplanetary propagation is translated in a broadening of the profile. However, of the diffusive nature of transport angular distribution is conserved.

IV. CONCLUDING REMARKS

Taking as working hypothesis features (5) and (6), we have developed a model capable of giving quantitative explanation of properties (1), (2), (3) and (4), and a qualitative description of properties (7) and (8). It is realized that solar longitudes with a high density of open field lines constitute preferential escape regions. However, we considered a constant escape rate due to our lack of knowledge of the coronal magnetic field distribution. Following property (6) we have solved the particle evolution equations in an energy independent manner. To give a quantitative explanation of property (7) we should have considered the parameter energy within our formulation. On the other hand, it should be noted that our analysis allows for a direct quantitative explanation of particle decrease, and delay of characteristic profile times, as suggested by property (8), if we introduce fluctuations in the values of the parameters K_ψ and V_d in equation (4).

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DISCUSSION

Pérez de Tejada: ¿Qué significa un "pico" en la distribución de partículas?.
Martinell: Que existe un escape de algunas partículas previo al máximo del flujo de protones asociados a una inestabilidad de desgarre (tearing mode). Esto ha sido puesto en evidencia por las observaciones de Van Hollebeke del grupo del GSFC.

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