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AZIMUTHAL PROPAGATION OF FLARE PARTICLES IN THE HELIOSPHERE

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ABSTRACT. A quantitative description of the coronal propagation of Solar flare particles is proposed. We adopt the conventional two-step model: convective transport inside a Fast propagation region (FPR) followed by a superposition of drifts and difusion outside the FPR with gradual escape to the interplanetary space. Solving the transport equations we obtain the time-intensity profiles and the azimuthal distribution of particles before their propagation in the interplanetary medium. The convolution of these results with a simple model of interplanetary propagation reproduces the general features observed at the orbit of the earth which are considered the indicators of coronal propagation. It is predicted that if the assumed FPR is an expanding magnetic bottle a Tearing-mode instability associated with a neutral current layer may appear: this would result in a new flux of energetic particles, the pick of which would be observed before the maximum of the flare particles.

1. Introduction: Coronal transport of solar flare particles before reaching the interplanetary magnetic field is now widely accepted. From several observational studies the main properties of coronal propagation have been deduced and can be summarized as follows: (1) The onset time and maximum time of the event increase with the angular separation between the observer and the flare site; (2) the azimuthal distribution of particles tends to be uniform in the late decay phase of an event; (3) the time-intensity profile widens when the angular distance from the observer to the flare increases; (4) the point of maximum intensity of particles moves in heliolongitude out of the flare site, besides property (2); (5) it has been inferred the existence of a fast transport process around the flare site which allows particles to cover a region of about 60°-100° of angular extension in one hour; (6) the transport of low and medium energy particles is accomplished in an energy and rigidity independent manner, although statistically it has been found a weak velocity dependence of the form $t_l \sim v^{-0.5}$ where t_l is the travelling time over a certain distance. However, the transport of high energy particles (100 MeV) shows an energy dependent

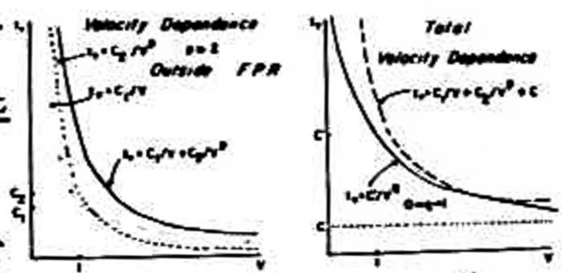


Figure 1

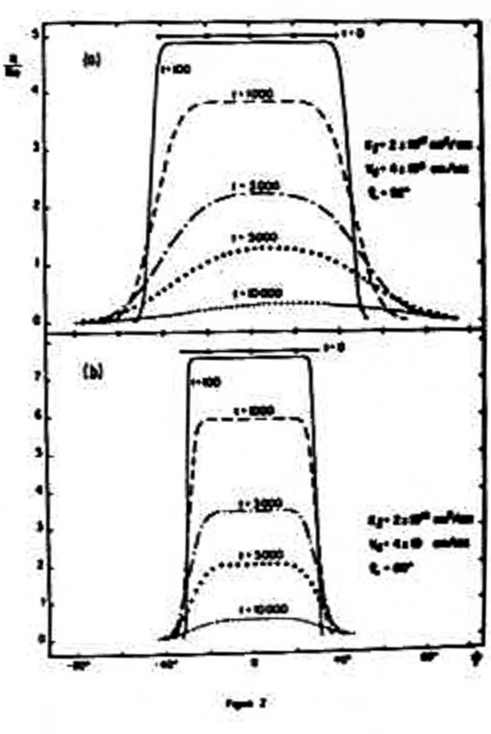
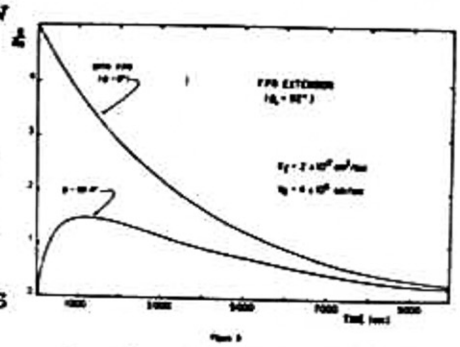


Figure 2



behavior; (7) the spectral index of the power law energy spectra increases with angular distance from the flare during the early phases of an event but sometimes it remains constant. During the decay phases the spectral index may decrease with angular distance; (8) the flare particles propagation is strongly influenced by the sector boundaries of the photospheric magnetic field, since particle-fluxes are decreased and the times of onset and maximum are increased when the observer is connected with solar region of opposite polarity to that of the flare region.

2. Transport Equations: We will attempt to give a quantitative description of coronal propagation based on some of the above properties. According to properties (2) and (3) the azimuthal transport is of a diffusive-like type, while property (4) suggests that a drift motion is also operating on the particles. These two mechanisms are velocity dependent; the first in the form $t_\ell \sim v^{-1}$ since the diffusion coefficient is proportional to the velocity ($K = 1/3\lambda v$, if the mean free path is independent of v); and the second according to Mullan and Schatten (1979) has a dependence of the form $t_\ell^{-1} \sim v^2/(1-v^2)^{0.5}$ which can be approximated by $t_\ell \sim v^{-p}$ ($p \geq 2$). Thus the superposition of these two processes gives a velocity dependence of the form $t_\ell \sim v^{-1} + v^{-p} \approx v^{-1}$. In order to conciliate this with the velocity dependence mentioned in property (6), we assume that within FPR the transport is achieved by a convective process independent of particle velocity (Schatten and Mullan 1977) and outside this region the drift and diffusion operate (Reinhard and Roelof, 1973). In this way, as illustrated in Figure 1, the total velocity dependence can be approximated by $t_\ell \sim v^{-q}$ with $0<q<1$. With this frame of work we will have two transport equations describing the evolution of particle density N. For simplicity we will use linear coordinates. Martinell and Pérez-Peraza (1981) have given the same analysis in spherical coordinates. Inside the FPR, the convection at a velocity V_c is described by the equation $\partial N/\partial t + V_c \partial N/\partial x = 0$ which has the solution $N(x,t) = (N_a/X_o)\delta(X - X' - V_c t)$, where N_a, X_o and X', are the number of accelerated particles, the FPR extension and the flare location respectively. We assume that this coherent motion takes place in all directions over the solar surface, so that when particles reach the boundary of the FPR to have covered all the extension of this region. Thus for the transport outside the FPR we have initially the condition $N(x) = N_a/X_o$ for $-X_o/2 < X < X_o/2$ and $N(x) = 0$ at the rest. The transport equation which governs the transport by drift at a velocity V_d and diffusion with a diffusion coefficient K_ℓ, and a escape of particles at a rate γ is $\partial N/\partial t = K_\ell \partial^2 N/\partial X^2 - V_d \partial N/\partial X - \gamma N$ which we assume is valid outside the FPR and at heigths for above of the FPR ($\geq 1.8\ R_\odot$). The solution of this equation with the initial condition given above is

$$N(X,t) = 2.5\ N_a \exp\left(-\gamma t - \frac{(X-V_d t)^2 - (X_o/2)^2}{8K_\ell t}\right)\left\{ \exp\left[\frac{(X-V_d t)X_o/2}{4K_\ell t} + \frac{(X-V_d t - X_o/2)^2}{8K_\ell t}\right] \mathrm{erf}\left(\frac{X-V_d t - X_o/2}{(4K_\ell t)^{0.5}}\right) - \exp\left[-\frac{(X-V_d t)X_o/2)}{4K_\ell t} + \frac{(X-V_d t + X_o/2)^2}{8K_\ell t}\right] \mathrm{erf}\left(\frac{X-V_d t + X_o/2}{(4K_\ell t)^{0.5}}\right)\right\} \quad (1)$$

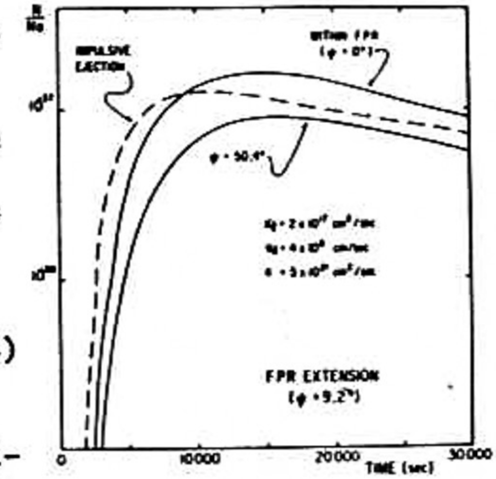


Figure 4

Figure 2 shows the distribution of particles in the corona given by equation (1) at different times, for two sets of values of the involved parameters. We have translated the linear coordinate equivalent in degrees as $\psi=(X/1.8\ R_{\odot})57.2957$. In Figure 2a the values of K_{ℓ} and V_d correspond to high energy particles and FPR extension of $\psi_o=92°$, while those of Fig. 2b correspond to low energy particles and $\psi_o=60°$. According to Reid(1964) we adopted a value of $\gamma=(3600\ s^{-1})$, however the results are not very sensitive on this parameter. We note that the maximum intensity is shifted out of the flare site, according to property (4), although this shift is not very noticeable at low energies,which indicates that diffusion dominates drift at low energies. It can also be seen that the distribution tends to be uniform for large times as indicated by property (2). In Fig.3 we show the time profile at two points, one within the FPR and other just outside the FPR, before propagation in the interplanetary space,for the parameters of Fig.2a. Here we also see that the intensity tends to be equal at the two points for large times, and that according to property (3) the profile widens with the angular distance from the flare. To obtain the time intensity profiles at the orbit of the earth we have made the convolution of the profiles of Fig. 3 with a simple model of interplanetary diffusion, with diffusion coefficient K along interplanetary field lines. For this model the particle density U is given by $U(r,t)=(4\pi Kt)^{-3/2}\exp(-r^2/4Kt)$ and then, the observed profile will be $W(r,\psi,t)=\int_0^t N(\psi,t-\tau)U(r,\tau)d\tau$ where τ is the interplanetary travelling time and $t-\tau$, the remaining time in the corona, with r=1.2A.U. the sun-earth distance along spiral field lines. In Fig. 4 we show the results of this convolution for the two profiles of Fig. 3. We can note here that the onset and maximum time increases with ψ as in property (1). For comparison we show the profile for pure interplanetary propagation, as if particles were impulsively ejected.

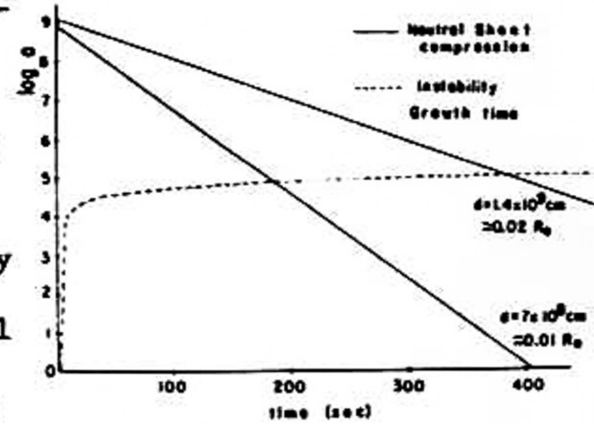


Figure 5

3. Prompt Particle Fluxes. If we adopt the model of Schatten and Mullan (1977) for propagation within the FPR independently of particle energy, we predict the presence of prompt particles before the flare particles can escape. Due to the complex magnetic structure of active regions the expanding magnetic bottle can get in touch with field lines of opposite polarity, forming a neutral point which becomes a neutral current sheet, because of the expansion of the bottle. Thus, a tearing-mode instability may be develcped and the field lines near the current sheet are reconnected transferring their energy excess to the thermal particles. Let us now estimate the growth time of the tearing-mode instability and to compare it with that of the Rayleigh-Taylor instability which allows the flare particles to escape from the bottle: according to Furth et al.(1963) the growth rate for a conductivity of $\sigma=10^{16}\ s^{-1}$, a plasma density $\rho=1.6\times10^{-13}\ gr/cm^3$,

and a field strength of B= 3 gauss is given by $\omega = 2.77\times10^5\ a^{-8/5}\ s^{-1}$, where a is the width of the current sheet in cm. This width decreases as $a = de^{-t/t_e}$ if we assume an expansion velocity of the bottle of the form $V = V_o e^{-t/t_e}$ where d is the initial width and $t_e = d/V_o$. Interpreting ω as the inverse of the growth time, we have plotted ω^{-1} in Fig. 5 and the variation of a for two values of d ($0.01\ R_\odot$ and $0.02\ R_\odot$). The intersection of these gives the actual growth time, and it turns to be 3 and 6 minutes for the two values of d. These are smaller than the Rayleigh-Taylor instability growth time of about 30 minutes (Schatten and Mullan, 1977) which implies that the new particles will be observed prior to the flare particles, at the point connected with the instability site.

4. Conclusion. We have developed a quantitative description of azimuthal transport which explains properties (1) to (4) of the introduction, and is in accordance with properties (5) and (6). A physical scenario for this model has been discussed by Martinell and Pérez-Peraza (1981). Concerning property (7) it may be argued that because the propagation processes are velocity dependent, the escape rate $\sim v^s$ may vary from a slight velocity dependence ($s< 1$) to a strong dependence ($s> 2$) such that, in the early phase of the event, this is translated in a nearly constant behavior of the spectral index with angular distance, to a strong dependence of the index with angular distance, in which case the more energetic particles escape earlier. In the decay phase the spectral index decrease with angular distance is associated with the effect of properties (2) and (4) on the escape rate. However a quantitative explanation of feature (7) implies the consideration of the energy equation within our formulation. In relation with feature (8) this may be explained by evoking the neutral current sheets lying along sector boundaries, in association with a similar process to that suggested by Fish and Schatten (1972) for modifications of fluxes due to the drift along the neutral sheet: this would imply the consideration of fluctuations in the values of K_ℓ and V_d. Finally it should be noted on Fig. 4, that the effect of interplanetary propagation is translated in a broadening of the profile, because the pure diffusive nature of the transport; however, angular distribution is conserved.

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ERRATA: In Fig. 3 it should be written within the FPR instead of with FPR,and in Fig. 1 should be written insted of t_ψ, t_ℓ.