INTERNATIONAL UNION
OF PURE AND APPLIED
PHYSICS

'87

August 2-15, 1987
Moscow, USSR

20th INTERNATIONAL COSMIC RAY CONFERENCE

HIGHLIGHT TALKS
MISCELLANEA
GENERAL INDEX

Moscow · NAUKA · 1988

Vol. 9

SIMULATION OF AZIMUTHAL TRANSPORT WITH EXPLICIT CONSIDERATION OF A CORONAL MAGNETIC FIELD TOPOLOGY

J.Pérez-Peraza*,M.Alvarez-Madrigal* and F.Rivero

Instituto Nacional de Astrofísica, Optica y Electrónica
Tonantzintla, A.P. 51 y 216, Puebla-72000,México

Abstract

The phenomenon of coronal azimuthal transport of solar flare particles is studied by numerical computation of individual particle trajectories, within the frame of the guiding center approximation. In contrast with previous analytical studies where the structure of the coronal magnetic field is not explicitely considered, here we consider a specific three-dimensional solar magnetic field topology. The predictions of this approach is discussed in terms of global observational effects.

Introduction. There is at present an established consensus that azimuthal description of solar particles takes place in the corona and not during interplanetary transport. The observational properties of such transport, and theoretical explanations of that phenomenon were extensively discussed in Pérez-Peraza (1986). An analytical model for this problem was developed by Pérez-Peraza and Martinelli (1981), and applied to some specific Multi-GeV solar proton events by Pérez-Peraza et, al.,(1985) and Pérez-Peraza (1986). This model describes the global observational features of coronal transport, and can be used to derive energy spectra of particles at the source level, or, at the level of particle injection from the corona, as well as time profiles and coronal azimuthal distributions of fluxes with no time cost for calculations. However, that analytical approach does not take into account the magnetic field structure of the coronal field, but instead it employs characteristic values of the particle transversal diffusion coeficient and particle drift velocity in the corona, which are usually worked out in the literature. Another approach to the problem of azimuthal transport is by following individual particle trajectories, in an specific magnetic field topology, which implies high expenses of computational time. In Pérez-Peraza et.al.(1987), a numerical approach was developed by solving the motion equations of particles in a simplified two-dimensional topology for the coronal magnetic field. In this work we present a faster numerical method to follow particle trajectories, using the guiding center approximation, but with a more realistic magnetic field topology.

2. Method. For solving particle trajectories in a given electromagnetic field,the fundamental equation which describes the particle behavior is given by the Lorentz equation

$$\bar{F}=(q/c)(\bar{v} \times \bar{B})+q\bar{E} \ , \tag{1}$$

where $\bar{v}$ is the particle velocity, q is the particle charge, $\bar{E}$ and $\bar{B}$ the electric and magnetic fields and c is the light speed. Neglecting any coronal electric field,so,

$$m\ddot{\bar{r}}=(q/c)(\bar{v}_{\parallel}+\bar{v}_{\perp})\times\bar{B} \ , \tag{2}$$

where $\bar{r}$ is the particle position vector, m is the particle mass, and

$$\bar{v}_{\perp}=\bar{v} \times \bar{B}/|B|$$
$$\bar{v}_{\parallel}=\bar{v}-\bar{v}_{\perp} \tag{3}$$

Since $\bar{E}$ is null the particle trajectory is a helix, describing a circular orbit about a fixed "guiding center", with gyroperiod

$$t=2\pi mc/q|B| \tag{4}$$

*Instituto de Geofísica, UNAM.

according to this description particle velocity along $\bar{B}$ is not affected by $\bar{E}$, i.e., $m\ddot{r}=0$, so $\dot{r}$ =Cte.= $\bar{V}$, from where

$$\int_{t_o}^{t} \dot{r}dr=\bar{v}_{\parallel}(t-t_o)=\bar{r}_{\parallel}-\bar{r}_{o\parallel} \qquad (5)$$

and so

$$\bar{r}_{\parallel}=\bar{r}_{o\parallel}+\bar{v}_{\parallel}(\Delta t) \qquad (6)$$

the equation set (3) gives the three components of $\bar{v}$, and (6) is then derived, component by component along $\bar{B}$. The employed magnetic field configuration was taken from Altschulerand Newkirk (1969), which in spherical cordinates is

$$B_{r'}=\sum_{n=1}^{\infty}\sum_{m=0}^{n}(n+1)(R/r')^{n+2}(G_n^m\cos m\phi+h_n^m\sin m\phi)P_n^m(\theta)$$

$$B_{\theta}=-\sum_{n=1}^{\infty}\sum_{m=0}^{n}(R/r')^{n+2}(G_n^m\cos m\phi+h_n^m\sin m\phi)\,dP_n^m(\theta)/d\theta \qquad (7)$$

$$B_{\phi}=(1/\sin\theta)\sum_{n=1}^{\infty}\sum_{m=0}^{n}m(R/r')^{n+2}(G_n^m\sin m\phi-h_n^m\cos m\phi)P_n^m(\theta).$$

Where ϕ and θ are the heliolongitude and heliocolatitude respectively, r' is the radial distance and R is the solar radius. The associated Legendre polynomials - $P_n^m(\theta)$ are functions of colatitude and the constants G_n^m and h_n^m must be determined from the photospheric magnetic data. Since we do not dispose of such data we arbitrarely setted $G_m^n=h_n^m=1$ Gauss. Hereafter B_o will indicate the measured line-of sight magnetic field around the flare region, that for the goal of illustration we arbitrarely fixed it to 30 Gauss.

For evaluation of v_x,v_y,v_z in (6).we assumed $v_x=v_y=v_z=v/(3)^{0.5}$. The velocity v is evaluated from the input energies in our computatational code. Equation (6) generates the equation set

$$\begin{aligned} X_{\parallel}&=X_{o\parallel}+v_{x\parallel}(\Delta t)\\ Y_{\parallel}&=Y_{o\parallel}+v_{y\parallel}(\Delta t)\\ Z_{\parallel}&=Z_{o\parallel}+v_{z\parallel}(\Delta t)\end{aligned} \qquad (8)$$

we have proceded to evaluate particle position along $\bar{B}$ every k gyroperiods, $k\Delta t=t_k$ where k=50 gives a good precision. So every evaluation of particle trajectory after k gyrocycles, the new position becomes the initial ($X_{o\parallel},Y_{o\parallel},Z_{o\parallel}$)position (the position is reseted). For the very initial positions where particles escape of the magnetic bottle,which characterize the fast propagation region (FPR),{For details of the model see Pérez-Peraza (1986)}, we setted r'/R=1.5, and ϕ and θ were derived from the position of the flare of August 22,1958 (10°W,18°N).Transformation of coordinates is made with $r'=(x^2+y^2+z^2)^{0.5}$; $\theta=\cos^{-1}(z/r')$;$\phi=\tan^{-1}(y/x)$. The relation $B_{r'}\sim B_0\csc\theta$ is filled during particle trajectories. According to the mentioned model the magnetic bottle of the FPR has a longitudinal extension of ±40°around the flare: particles ejected when the bottle opens propagate basically in azimuth while leaking radially into the interplanetary space at r'≈2.2R. Therefore,for the evaluation of trajectories of particles that leave the corona, we limit our particle counting to those particles which reach 2.2R within the - range 100°S≤θ≤100°N and the range 100°E≤θ≤ 100°W. For derivation of particle energy spectra at a given coronal latitud (60°W for instance) from a limited number N of sample particles, we have proceeded by counting the number $n(E_i,\phi i)$ of particles of energy E_i that escape at ~2.2R by longitud ϕ_i, such that for each E_i we evaluate $n(E_i,\phi_i)^i\{N_s(E_i)/N\}$, where N_s (E_i) is obtained from the source energy spectrum at the flare level, given by Pérez-Peraza (1986) for the August 22, 1958 event: $N_s(E)=1.72\times10^{45}E^{-6.18}$(protons/MeV).For the goal of computational economy in time we typically use N=100-200. The evaluation of particles trajectories allows us for derivation of azimuthal distribution of particles leaving the corona at r'=2.2R. Also, for a given longitude and fixed energy the time profile at the level of the roots of the interplanetary magnetic field lines may be built.

3. Results and Discussion. First of all it must be pointed out that as must of numerical methods, this has several limitations in the sense that the precisness of results is proportional to the number of gyroperiods, which in turn is proportional to the computational time. Also our results are highly sensitive not only to the shape of the magnetic field topology but to the field strength of its components.

In spite of all these limitations, the obtained results reproduce some of the observational features of coronal azimuthal transport, as for instance, the displacement of the peak intersity, in the coronal azimuthal distributions of fluxes, toward longitudes farest from the FPR, as time elapses, what is usually attributed to particle drift in heliolongitude. Also the obtained time profiles show the typical diffusive shape, and the energy spectrum at a given time becomes flatter with heliolongitudinal distance from the FPR (which of course, is centered around the flare site). In addition, the numerical method has the advantage over our analytical model that it allows for the evaluation of individual particle trajectories. On Fig. 1 it is illustrated the trajectories of two protons of 70 MeV which are ejected from different places of the top of the FPR, when it blows open at r'=1.5R: one of them travels to the East and the other to the West, ending by escaping at r'=2.2R. The qualitative difference between the analytical and the numerical method, is that the later does not furnish a continuos azimuthal distribution, but rather a discrete one, as can be seen in Fig. 2 for two different times; this is due to the nature of the magnetic field topology, because particles escape in a preferential form where the field lines are open, or, the field strength is relatively weak: the magnetic field intensity of two field components is shown on Figs. 3 and 4, where it can be appreciated that the regions of weakest B_r, are precisely the place where more particles are counted. Fig. 5 shows the smoothed time profiles from the discrete values obtained at ϕ=60° and 80°W, in terms of arbitrary scales. Fig. 6 shows the energy spectrum computed at 60°W and 80°W together with the source energy spectrum of the August 22, 1958 event. First of all it can be appreciated that according to observations, the spectrum is flatter with azimuthal distance from the flare. However the spectrum obtained at $60^{o}WN(E)\sim E^{-4.2}$ is steeper than the demodulated spectra of data by Miroshnichenko and Petrov (1985) (see also Alvarez-M. et al 1986), which at the level of the roots of the interplanetary field lines is $N(E)=3.7\times10^{39}E^{-3.63}$(protons/MeV). Our result constrastes with our previous numerical evaluations (Pérez-Peraza et, al, 1987) where we found γ=3.59.

We conclude that the method is very powerful and cheap when the specific parameters of the field topology is known during an specific solar particle event, in which case predictions may be directly confrontated with observational data.

References

1. Altschuler, M.D. and Newkirk, G. Jr, 1969, Solar Phys. 9, 131.
2. Alvarez-M., Miroshnichenko, L.I., Pérez-Peraza, J. and Rivero-G, E., 1986, Soviet Ast. 63-6, 1169.
3. Pérez-Peraza, J. and Martinelli, J. 1981, Proc. 17th Int. Cosmic Ray Conf. 3, 55. Pérez-Peraza, J., 1986, Space Sc. Rev. 44, 91.
4. Pérez-Peraza, J., Alvarez-M., and Rivero, F., 1987, R.M.A.A. 14.