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NUMERICAL ANALYSIS OF THE AZIMUTHAL TRANSPORT OF SOLAR PARTICLES

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

Instituto Nacional de Astrofísica, Optica y Electrónica
Tonantzintla, Pue., México

RESUMEN. El estudio de la propagación coronal de las partículas generadas en las Fulguraciones Solares, se ha llevado a cabo mediante técnicas analíticas, a manera de describir aspectos globales del fenómeno. Sin embargo, el detalle concerniente a la estructura del campo electromagnético coronal a través del cual se transportan azimutalmente las partículas antes de alcanzar el espacio interplanetario, no ha sido considerado hasta ahora. En este trabajo se incorpora el detalle de la estructura del mencionado campo electromagnético, dentro del marco del modelo de transporte coronal desarrollado con anterioridad. A partir de la comparación de los espectros derivados en este trabajo, con los espectros que se obtienen por demodulación interplanetaria de datos de protones a nivel de la órbita terrestre, es posible inferir acerca de la topología magnética del campo coronal.

ABSTRACT. Until now we have developed analytical methods to describe global features of the phenomenon of coronal azimuthal transport of particles generated in Solar Flares. However, the detail of the coronal magnetic field through which particles propagate azimuthally in the corona before reaching the interplanetary medium has not been considered. Here we consider the details of the magnetic field structure within the frame of the scenario that we previously proposed. The developed model in this work is numerically solved. We derive particle energy spectra at the level of the roots of the coronal magnetic field for two specific solar proton events. From the confrontation of these spectra with those derived from interplanetary demodulation of solar proton data at the level of the earth level, we are able to infer about the large-scale coronal magnetic field topology.

Key words: SUN-PARTICLES

I. INTRODUCTION

Solar particles leaving the source environment need to travel through two different magnetic field topologies, namely those of the corona and the interplanetary medium. Though, in some particular events it may occasionally occur impulsive ejection of particles from the source to the base of the interplanetary magnetic field lines, in general, there is a gradual particle control by coronal magnetic fields, in such a way that particles distribute in heliolongitude while escaping to the interplanetary space. At present, there is an established consensus that the azimuthal distribution of solar particles takes place mainly in the corona, not during interplanetary transport. The observational properties of azimuthal transport and evidences that it takes place at the coronal level were exhaustively discussed in Pérez-Peraza (1986). It is now realized that particle profiles, anisotropies, longitudinal distributions and modulation of the source energy spectrum are determined during both coronal and interplanetary transport. In order to understand

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* Instituto de Geofísica, UNAM.

the coronal azimuthal transport of flare particles, we develop an analytical model Pérez-Peraza and Martinelli (1981); and Martinelli and Pérez-Peraza (1981), which physical scenario was widely discussed by Pérez-Peraza (1986).

For an observer along the magnetic flux tube which connects the Sun to the Earth, two different kind of events are observed: first, if the so called Fast Propagation Region (FPR) of particles, at ∿±35° of the flare site encloses the Sun-Earth connecting field line (located at 60° W), therefore, the observed properties of particle fluxes are in some extent representative of particle properties at the source level. In this case, it is expected that the source energy spectrum of particles is not modulated in the corona, since according to observational properties (and so to our model predictions) particle propagation within the FPR is energy independent; if it is assumed that collisional energy losses are negligible (thin geometry) within the time scale of particle residence within the FPR, only interplanetary modulation is important. The other kind of events are those where the Sun-Earth connecting heliolongitude is out of the FPR, so that particles that eventually reach that connecting heliolongitude need to travel azimuthally in the corona, from the flare site to that point: according to observational evidences, this kind of azimuthal propagation and the gradual particle escape into the interplanetary medium during the coronal propagation, present a slight energy dependence. In this case, the observator along the connecting magnetic flux tube between the sun and the earth, detect particle fluxes that have been modulated at both levels, in the corona and in the interplanetary space.

Applications of the analytical model to some specific solar particle events were done in Pérez-Peraza et.al. (1985) and Pérez-Peraza (1986): demodulation of particle data (measured at the level of the earth orbit) by the method of Miroshnichenko and Petrov (1985) based on to the particle interplanetary propagation model of Krimigis (1965) allows to extrapolate that data back to the roots of the interplanetary magnetic field lines. With the knowledge of particle fluxes at that level, we can build the energy spectrum of particles at the coronal site of the magnetic sun-earth connection (60°W). Once we know the spectrum at that coronal site, we can build with our analytical model the energy spectrum of particles at other different coronal heliolongitudes at the time of their escape into the interplanetary medium. From the coronal roots of the interplanetary magnetic field lines, we demodulated those fluxes for coronal azimuthal transport, such to turn back to the FPR. Since according to the previously discussed arguments, the particle source energy spectrum has not been modulated during transport from the source to the escape of the FPR, but only diluted, we applied a correction for such a dilution, and thus we claim to have derived source energy spectra in this form. In those two works we have employed our analytical model not only to derive azimuthal distribution of particles, time profiles and spectra at coronal level, but also the source energy spectra as we just described.

The knowledge of the source energy spectrum of solar particles, is of fundamental importance in Solar Physics for many reasons; it can be mentioned, for instance, because the shape of the spectrum contains information regarding the acceleration mechanism of particles, because solar particles contain as much energy as the total energy of electromagnetic field radiation, because the accelerated particles are involved in several atomic, electromagnetic and plasma processes in the solar atmosphere, etc.

Although it is true that our analytical model describes the global features of coronal azimuthal transport of particles, and can be used to derive energy spectra of particles, time profiles and azimuthal distributions of fluxes with no time cost for calculations, however, we must keep in mind that this approach is in some extent a simplification of the real phenomenon: in fact, this analytical approach does not take into account the magnetic field structure of the coronal field, but instead, it employs some characteristic parameters of particle transport in electromagnetic fields, namely the particle drift velocity and the transversal diffusion coefficient, whose typical values have been worked out in the literature. Another approach to the problem is the calculation of trajectories of individual particles in an specific magnetic field topology of the corona. To do so, it is needed the numerical solution of the motion equations in that topology, which implies high expenses of computational time. In this work, we develop the numerical approach of our model for calculations of energy spectra at the coronal level of two solar particle events; starting with the source energy spectrum derived in our analytical approach we leave particles to propagate until they reach the sun-earth connection heliolongitude. The obtained spectrum may be compared with the spectrum which is obtained from interplanetary demodulation of observational data. If the agreement between both spectra is good, it means that both approaches are quite similar , and therefore, for the goal of computational economy, the analytical approach may be used with a high degree of confidence for studies of coronal azimuthal transport of solar particles. On the other hand, the numerical approach has also the advantage to give in formation about the kind of magnetic topology prevailing at the corona, by the time of an specific solar event:by testing different magnetic field topologies in the numerical process of reproducing the coronal "semi-observational" spectrum (demodulated from observational data) we can infer about the adequate topology.

II . THEORY OF THE NUMERICAL APPROACH

For solving particle trajectories, the fundamental equation which describes the particle behavior in an electromagnetic field is given by the Lorentz force

$$\overline{F} = q\ [\overline{E} + 1/c\ (\overline{v} \times \overline{B})] \tag{1}$$

where $\overline{v}$ is the particle velocity, q is the particle charge, $\overline{E}$ and $\overline{B}$ are the electric and magnetic fields respectively and c is the light velocity. To board our specific problem we make the following assumptions:

(1) The solar general magnetic field is a dipole.

(2) In a first approximation, azimuthal transport may be reduced to a bidimensional problem of motion in heliolongitude, neglecting particle motion in heliolatitude ($v_z = B_z = 0$).

(3) The main coronal magnetic topology in the "Low Propagation Region" (out of the FPR) is constituted by coronal magnetic loops, which are coplanars with any azimuthal plane parallel to the equator.

(4) The electric field is null along particle trajectories in azimuth.

Concerning the third assumption, it is well known that superimposed to the background magnetic - topology of coronal loops, it may be Helmet Streamers, and that sector boundaries are present; - however, in this first analysis we neglect these structures that we consider of second order in importance. With regard to the last assumption, electric fields may be created in neutral current sheets, when two loops of opposite polarity approach very close among them, so that a diffusion region is formed, where the plasma diffuse toward the neutral line with velocity V_d. In this region an electric field $\overline{E} = 1/c\ \overline{V}_d \times \overline{B}$ is generated. Since according to our assumptions - $\overline{V}_d$ and $\overline{B}$ are in the same plane of azimuthal propagation, constructed by $\hat{e}_x$ and $\hat{e}_y$, therefore $\overline{E}$ is in the orthogonal plane, in the $\hat{e}_z$ direction.

Under the last considerations, the equation set to be solved is

$$\ddot{X} = -\frac{q}{mc} B_y \dot{Z} \tag{2}$$

$$\ddot{Y} = \frac{q}{mc} B_x \dot{Z} \tag{3}$$

$$\ddot{Z} = \frac{qE}{m} + \frac{q}{mc} (B_y \dot{X} - B_x \dot{Y}) \tag{4}$$

where $B_x = \overline{B} \cdot \hat{e}_x$, $B_y = \overline{B} \cdot \hat{e}_y$, $E = \overline{E} \cdot \hat{e}_z$ and m is the particle mass (in this case the proton mass). Considering that the magnetic configuration does not change during the time scale of azimuthal propagation of particles, we obtain two more equations

$$\dot{X} = -\frac{q}{mc} B_y (Z - Z_o) + \dot{X}_o \tag{5}$$

$$\dot{Y} = \frac{q}{mc} B_x (Z - Z_o) + \dot{Y}_o \tag{6}$$

substitution of Eqs. (5) and (6) in Eq. (4) gives

$$\ddot{Z} = -\frac{q^2}{m^2c^2} (B_x^2 + B_y^2) Z + \frac{q^2}{m^2c^2} (B_x^2 + B_y^2) Z_o + \frac{qB_y}{mc} \dot{X}_o - \frac{qB_y}{mc} \dot{Y}_o + \frac{q}{m} E \tag{7}$$

setting $P = -\frac{q^2}{m^2c^2} (B_x^2 + B_y^2)$ and $K = \frac{q^2}{m^2c^2} (B_x^2 + B_y^2) Z_o + \frac{qB_y}{mc} \dot{X}_o - \frac{qB_y}{mc} \dot{Y}_o + \frac{q}{m} E$, Eq. (7) reduces to the - form

$$\ddot{Z} + PZ = K \, , \tag{8}$$

whose solution is

$$Z = A \cos(P^{0.5} t + \phi_o) + K/P. \tag{9}$$

The integration of Eqs. (5) and (6) with substitution of Eq. (9) gives

$$X = -\frac{qB_yA}{mc\,P^{0.5}} [\sin(P^{0.5} t + \phi_o) - \sin(P^{0.5} t_o + \phi_o)] + [\frac{qB_y}{mc} (Z_o - \frac{K}{P}) + \dot{X}_o] (t - t_o) + X_o \tag{10}$$

and

$$Y = \frac{qB_xA}{mcP^{0.5}} [\sin(P^{0.5} t + \phi_o) - \sin(P^{0.5} t_o + \phi_o)] + [\frac{qB_x}{mc} (\frac{K}{P} - Z_o) + \dot{Y}_o] (t - t_o) + Y_o \tag{11}$$

the values of A and ϕ_o are given by the initial conditions at $t = t_o$; $Z(t_o) = Z_o$ and $\dot{Z}(t_o) = \dot{Z}_o$ as follows

$$\phi_o = \arctan \left(\frac{\dot{Z}_o P^{0.5}}{K - Z_o P}\right) - P^{0.5} t_o \tag{12}$$

$$A = \frac{Z_o - K/P}{\cos(P^{0.5} t_o + \phi_o)} \tag{13}$$

Now, for numerical evaluations of particle trajectories we employed a similar analysis to the well known Box-wise method, but instead of boxes with B=constant, here we have that the magnetic field is constant in a fraction of gyro-radius (or in several gyro-radius depending on the solution convergence), so that we apply our analytical solutions derived above only in this trajectory fraction; next, we add several of these partial solutions to form a complete particle trajectory.

III. METHOD

For the goal of illustration we have chosen two solar proton events, the February 22, 1958 event where the coronal spectrum is known from interplanetary demodulation of data, and the source spectrum was derived by the analytical method in Pérez-Peraza et.al. (1985). On the other hand, the event of November 9, 1979 where the source spectrum is known in the literature from gamma-ray lines measurements, and the coronal spectrum was derived in Pérez-Peraza (1986). The flare sites of these events were 10°W and 2°W respectively; this implies that their respectives FPR do not involve the heliolongitude of the sun-earth magnetic connection, and thus particles that were seen at the earth orbit needed to propagate to the 60°W position where they reach the interplanetary field lines. Let us remember that according to the theoretical concepts, the FPR is associated with some kind of closed magnetic configuration, in the form of an expanding magnetic bottle that opens at some specific height depending on the prevailing kinetical and hidromagnetical conditions during each event. We assume here that the FPR opens at $1.5R_\odot$ with a longitudinal extension of ±40° around the flare. The particle energy spectrum at the opening of the FPR is the same through all the FPR extension, because the source spectrum at the flare level is uniformely distributed on the top of the FPR, after dilution during the convective magnetic and plasma expansion.

For the task of simplicity we have applied a transformation from cartesian to polar coordinates. Therefore, the employed magnetic field configuration to describe the large-scale magnetic loops is

$$B_x = \frac{B_o}{(R/R_\odot)^2} \sin(k\theta + \psi) \tag{14}$$

$$B_y = \frac{B_o}{(R/R_\odot)^2} \cos(k\theta + \psi) \tag{15}$$

where R is the radial position in heliocentric units, θ is the heliolongitude and $R_\odot$ is the solar radius. For the August 22, 1958 event, we considered $B_o = 10$ gauss, $k = 3$ and $\psi = -70°$; whereas for the November 9, 1979, $B_o = 10$ gauss, $k = 4$ and $\psi = -50°$. These values of ψ were fixed by rotation of the magnetic field configuration until one obtains the largest azimuthal displacement of particles, as indicated by observational evidences.

The employed energy range of particles are: (20 - 140) MeV for the August 22, 1958 event and (30 100) MeV for the November 9, 1979 event. The energy of particles at the liberation from the FPR was distributed in similar parts between the radial and the tangential velocities. For practical purposes we used in our calculations seven different energies as typical samples of the respective energy range. For everyone of these selected energies we left to run two hundred particles from different positions of the top of the FPR. We considered that the magnetic field is constant during one hundred particle gyroperiods, that is, particle positions were controlled every one hundred gyroperiods, until particles reach $2R_\odot$, where we assume that the magnetic field is not any more in the form of loops but open lines into the interplanetary space. It is precisely at $2R_\odot$ where we have fixed the coronal roots of the interplanetary field lines, and so, it is at this level that we calculate the coronal energy spectrum, coronal time profiles and azimuthal distributions.

For the calculations of coronal spectra, $N(E) = D_o E^{-\gamma}$, we have proceeded as follows:

(a) We select from each energy those particles whose trajectories cross the heliolongitude of 60° ± 3°W at a radial position of $2.1 \pm 0.2R_\odot$.

(b) We assume that the sample particles of a given energy are representatives of the total number of particles of that specific energy in the source energy spectrum.

(c) Under assumption (b) we assign to particles of (a) an statistic weight.

(d) We take the logarithms of the coordinates obtained from (c) and then we apply a geometrical regression to that values for obtaining D_o and γ of the spectrum.

Therefore, starting from a given source energy spectrum at the level of the top of the FPR (which has been diluted relative to the flare level, but not modulated) we left particles to propagate azimuthaly and then we determine which is the particle spectrum at ∿ 60°W, at the level of particle injection in the interplanetary space.

IV. RESULTS AND CONCLUSIONS

On Fig. 1 it is shown for the August 22, 1958 event the trajectories of six different energies, when the magnetic field configuration is not rotated ($\psi = 0°$). In order that particles reach the 60°W position at ∿ $2R_\odot$, they need to be ejected from the extreme west of the FPR; particles of the rest of the FPR extension scarcely reach that position, under such magnetic topology. Therefore, we rotated the configuration to a value of $\psi = -70°$ and results are shown in Fig. 2. Here it can be appreciated that particles ejected from about 15° of the extreme west of the FPR arrive to the sun-earth connection at 60°W. For the same solar event, we show in Figs. 3 and 4 the trajectories of protons of a given energy (80 MeV) ejected every 10° within the 80° of the FPR extension, without rotation and with rotation of the magnetic configuration respectively. On Fig. 5 we illustrate the obtained coronal spectrum at 60°W with the rotated magnetic topology, together with the source spectrum at the level of the flare. On Figs. 6, 7 and 8 we illustrate the same effects for the November 9, 1979 solar event for a rotation with $\psi = -50°$.

It must be pointed out that this numerical method has several limitations: first of all, the method is highly sensitive to the number of gyroperiods where the magnetic field is held constant. In other words, the smaller number of gyroperiods (or the shorter piece of trajectorie), the higher precision of the results, with the subsequent increase of the computational time. Also, our results are highly sensitive not only to the shape of the magnetic field topology, but to the place where it is centered, as was shown with the variation of results with the rotation of the configuration. In addition, results become sensitive to the number of sample particles ejected from the top of the FPR; the higher the number of sample particles, the higher the precision in the determination of the D_o and γ values of the spectrum. Therefore, since the task of determining in each solar event the convergence in the number of gyroperiods and of the sample particles needs very important computational times, we have fixed the respective values at the level where our results begin to stabilize On the other hand, this approach is also limited in the sense that the problem has been reduced to a bidimensional propagation phenomenon, and that any kind of coronal magnetic structures different to coronal loops have been neglected.

In spite of all these limitations, the obtained results lead to very interesting conclusions:

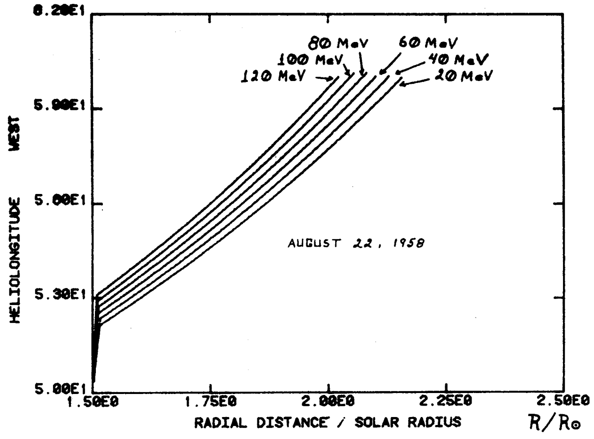

Fig. 1. Trajectories of Particles.

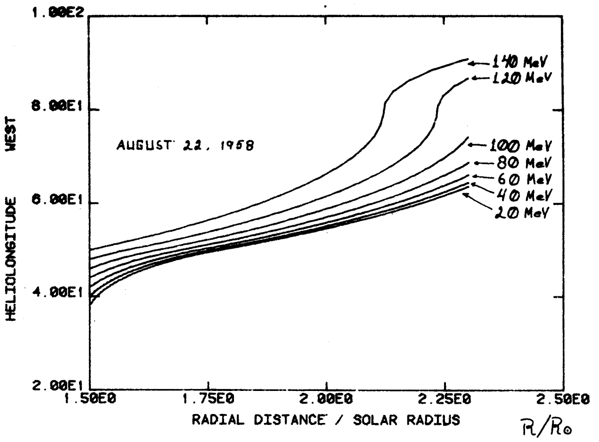

Fig. 2. Trajectories of Particles.

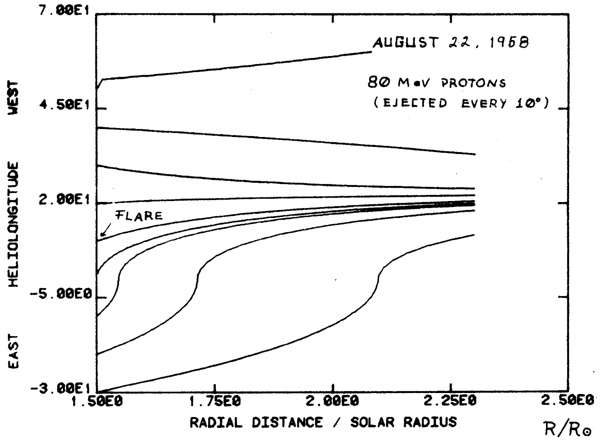

Fig. 3. Trajectories of Protons.

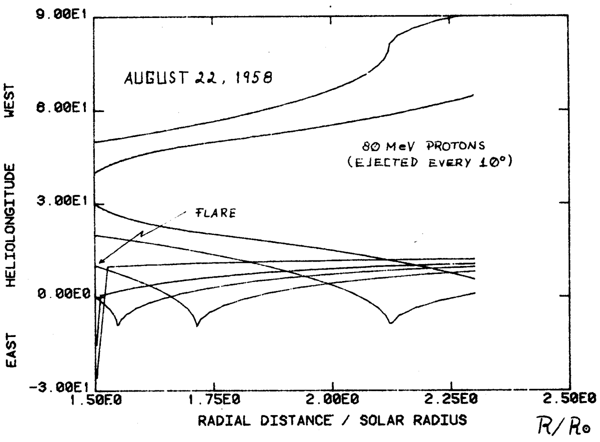

Fig. 4. Trajectories of Protons.

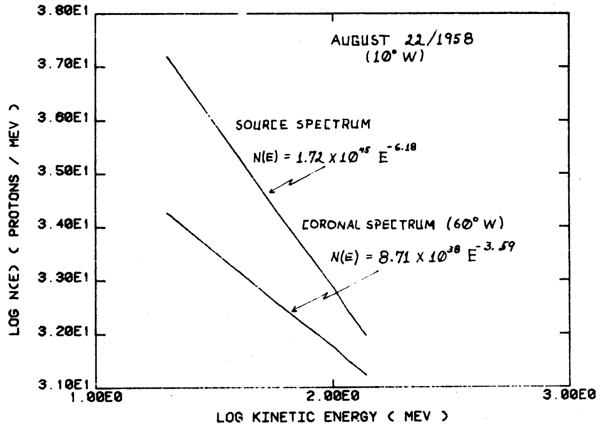

Fig. 5. Coronal Spectrum.

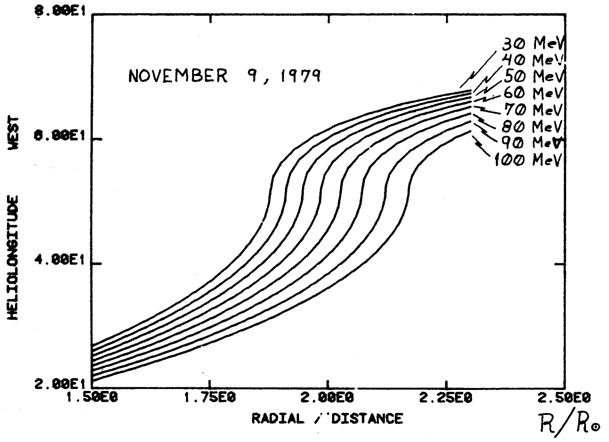

Fig. 6. Trajectories of Particles.

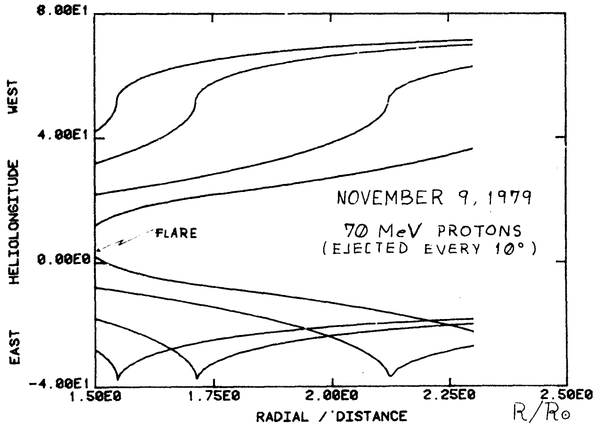

Fig. 7. Trajectories of Protons.

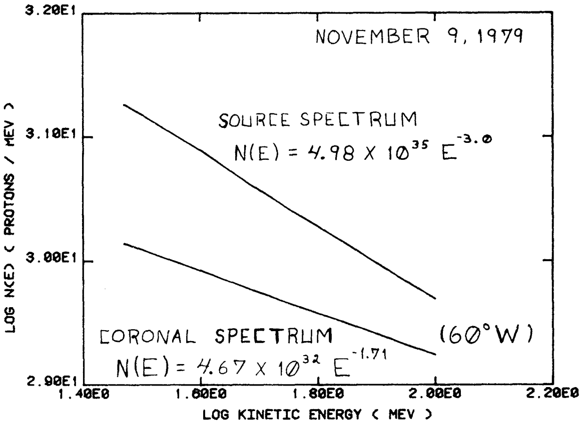

Fig. 8. Coronal Spectrum.

The fact that the derived coronal spectra of the August 22, 1958 event, $N(E) = 8.7 \times 10^{38} E^{-3.59}$, is close to the coronal spectrum derived from interplanetary demodulation of data, $N(E)_{im} = 3.7 \times 10^{39} E^{-3.63}$ means that, (a) the derived source energy spectrum by the analytical approach - (that is used here as the initial spectrum of the ejected particles) is quite realistic, since - after coronal modulation it turns to be of the precise order of magnitude as the coronal spectrum derived from data, and this argues in favor of the analytical method. (b) the similarity between the results of the numerical and analytical methods implies that for the task of computational economy, the analytical method is a very useful tool to be employed when the details of the magnetic field structure and of individual particle trajectories might be neglected. (c) the fact that the best approach between $N(E)_{cm}$ and $N(E)_{im}$ is obtained with the employed magnetic topology allows to infer about the realistic field topology prevailing during this event.

From the relatively good agreement between the derived coronal spectrum of the November 9, 1979 solar event with the coronal spectrum derived with our analytical method in Pérez-Peraza (1986), we may conclude the following: (a) since the initial source spectrum is of observational nature, and both the analytical and numerical methods lead to a similar coronal spectrum, then the - derived coronal properties from our model of coronal azimuthal transport are highly confident. (b) the analytical approach may be used when economy of computational time is required. (c) very reliable information about coronal magnetic field topology may be infered from the numerical approach.

Summarizing, the developed numerical analysis of coronal azimuthal transport of solar flare particles has shown to be very useful for evaluating the degree of accuracy of the analytical method, for evaluation of individual particle trajectories in the solar corona and to draw information about the magnetic field topology of the corona during a given solar event.

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Manuel Alvarez-Madrigal and Jorge Pérez-Peraza: Instituto de Geofísica, Universidad Nacional Autónoma de México, 04510 México, D.F., México.
Fausto Rivero: Instituto Nacional de Astrofísica, Optica y Electrónica, Apartados Postales 51 y 216, 72000 Puebla, Pue., México.