Spectrum of solar cosmic rays in the source with allowance for their coronal propagation

M. Alvarez-Madrigal, L. I. Miroshnichenko, J. Pérez-Peraza, and F. Rivero-Garduso

Instituto de Geofisica, Universidad Nacional Auton. de Mexico,
Instituta Nacional de Astrofisica, Optica y Electronica, Puebla, Mexico,
and Institute of Terrestrial Magnetism, the Ionosphere, and Radio-Wave Propagation, USSR Academy of Sciences

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A model of coronal propagation is considered that includes convective particle transport near the flare and diffusion and centrifugal drift at large solar longitudes. Data on the spectra of solar cosmic rays (SCR) for a number of solar proton events (SPE) are analyzed on the basis of this model. On the example of the SPE of August 22, 1985, the main consequences of the model are illustrated: 1) a clear picture of the evolution of the SCR spectrum during propagation in the corona; 2) flattening (hardening) of the emission spectrum in comparison with the spectrum of the source; 3) an east-west asymmetry in the azimuthal distribution and time profile of particles of a given energy; 4) practical coincidence of the emission spectrum with the spectrum of the source within fast-propagation region. Observed and calculated characteristics of the spectra for 12 SPE are given, mainly for proton energies of $\lesssim 100$ MeV.

1. INTRODUCTION

Data on the energy spectrum of solar cosmic rays (SCR) in the source, i.e., data on the absolute flux of SCR and the form of their spectrum in the acceleration region (in a solar flare), are of great interest for at least three reasons: 1) The accelerated particles contain a total energy comparable with the total energy of the electromagnetic emission of the flare[1] ($\sim 10^{31}$ erg); 2) the form of the spectrum indicates the possible mechanism (or mechanisms) of acceleration[2]; 3) the accelerated particles participate efficiently in nuclear, electromagnetic, and plasma processes in the solar atmosphere.[3] Consequently, data on SCR spectra in the source are required for the theoretical description of these processes, for the formulation of a self-consistent model of a solar flare, and for probing the properties of the source itself.

The reconstruction of SCR spectra in the source from observations near the earth's orbit is a complicated problem, since the spectrum undergoes considerable modulation along the way from the source to the earth. According to modern concepts, the observed time profile of the intensity is a superposition of the effects of propagation in the solar corona and interplanetary space.[4]

Because of the stochastic nature of the interplanetary magnetic field (IMF), the inverse problem of SCR propagation in interplanetary space (i.e., the reconstruction of their characteristics near the sun from observation at the earth) cannot be solved exactly; it can only be solved in certain model approximations. For this one must assume that the demodulated spectrum corresponds approximately to the spectrum of the emitted particles in the upper corona near the longitude of connection between the sun and the earth ($\theta \approx 60°$ W). For further demodulation of the spectrum to the region of acceleration, one must allow for the transport of accelerated particles in the magnetic fields of the solar atmosphere. Below we attempt to analyze this problem within the framework of the model of coronal propagation of Refs. 5-7, using data of a catalog of SCR spectra near the sun.[8]

2. FEATURES OF CORONAL PROPAGATION

A list of the most characteristic features of coronal propagation is given in the review Ref. 7.

1) The time of onset and the time of the intensity maximum of SCR increase (or at least remain constant) with an increase in the azimuthal distance θ between the solar longitude θ_f of the flare and the solar longitude θ of connection between the earth and the sun;

2) the time profile of the intensity broadens in this case;

3) the azimuthal distribution of the particles has a tendency to become more uniform with time in the phase of decay of solar proton events (SPE);

4) azimuthal transport in the corona takes place with two different velocities: about 50° h^{-1} (the FPR or fast-propagation region with a size of ~ 60-100° around the flare) and 20-93° per day (the SPR or slow-propagation region);

5) the azimuthal propagation of low-energy particles hardly depends on their hardness R or energy ε_c, but the transport time is $t_\theta \propto v^{-0.55}R^{-0.07}$, where v is the particle velocity; high-energy particles display a tendency toward a decrease in t_θ with an increase in ε_c;

6) azimuthal propagation is controlled to a certain extent by the boundaries of sectors of the large-scale unipolar magnetic field on the photosphere;

7) the peak of intensity shifts toward the west in longitude from the flare by one and the same distance ($\sim 100°$ for the SPE of April 10, 1969), where the shift ceases;

8) for $\varepsilon_c \gtrsim 15$ MeV the exponent γ_ε of the spectrum grows with an increase in azimuthal distance in the initial stage of an SPE, whereas in subsequent stages γ_ε remains constant, although in certain cases γ_ε decreases with longitude in the decay stage;

9) in certain cases the decay stage has two phases, and the decay time constant suddenly increases by a factor of two to three in the transition from one phase to the other;

10) in certain cases the duration of particle emission exceeds the time required for ordinary azimuthal propagation of the particles;

11) at least in the particular case of corotating SPE, when a regime of continuous emission is established, the intensity decay time for low-energy particles is longer than for high-energy particles (see

the corresponding references and commentary in the review of Ref. 7 for more detail).

The first seven characteristics are more or less general for the majority of SPE, while the rest have a more particular, specific character. The first three properties suggest typical diffusional transport, but the time of the intensity maximum grows linearly with azimuthal distance, rather than quadratically.

In the modeling of coronal transport one must explain qualitatively and quantitatively the observational data enumerated in paragraphs 1-11, i.e., reveal the physical processes determining particle transport in the corona and give an adequate mathematical description of the influence of these processes on the temporal and spectral characteristics of SCR. As was shown in Ref. 7, at present none of the existing models can satisfactorily reflect both aspects of coronal transport. The majority of the models proposed earlier were aimed at explaining individual events or a series of specially selected SPE. It seems reasonable to us first to develop a general methodology adequate to the physical processes of particle transport and then, within the framework of a certain mathematical model, to explain the specific features of individual SPE. A preliminary attempt at such an approach[9] proved to be fully justified and quite fruitful

3. MODEL OF CORONAL TRANSPORT

As was shown in Refs. 5-7, for a consistent interpretation of the observational data 1-11 one must assume that the process of coronal propagation of SCR consists of two stages. In the first stage most of the accelerated particles ($\varepsilon_c < 100$ MeV) are transported coherently through the FPR to its boundaries independently of particle velocity. The second stage depends on the particle velocity, with transport taking place in the SPR through transverse diffusion and centrifugal drift with the gradual escape of particles into interplanetary space.

Coherent (convective) transport can be accomplished either by a flare shock wave[10] or by an expanding magnetic structure connected with closed magnetic loops above a flare.[11] In other words, in analyzing particle transport in the FPR we must allow for the dynamic character of the coronal magnetic fields. On the basis of the model of Ref. 11, and taking the transport velocity as V_c, we can write a simple equation of conservation of the number of particles inside the FPR,

$$\frac{\partial N}{\partial t} = -\frac{V_c}{r_a}\frac{\partial N}{\partial \theta}, \tag{1}$$

where $N(\mathbf{r}, t)$ is the particle concentration at the point $\mathbf{r}$ at the time t. It is assumed that the particle transport takes place in a layer with a radius r_a concentric with the sun, and V_c can reach values of 250-400 km·sec^{-1}. Although the propagation occurs isotropically, only longitudinal effects can be detected, since flares are observed in a relatively narrow interval of solar latitudes, while the majority of observations of SPE are made in the ecliptic plane.

The solution of Eq. (1), yielding a coherent "packet" of particles in the azimuthal direction, has the form

$$N(\theta, t) = \frac{N_a}{4\pi r_a^3 (1-\cos\theta_0)}\,\delta\left[\frac{r_a}{V_c}(\theta-\theta_f)-t\right], \tag{2}$$

where N_a is the number of accelerated particles, δ is the delta function, and θ_0 is the extent of the FPR. The convective flux is distributed uniformly over the entire top of the FPR, so that the initial condition for particle propagation outside the FPR can be written as

$$N(\theta, 0) = \begin{cases} \dfrac{N_a}{4\pi r_a^3(1-\cos\theta_0)}, & |\theta| \leqslant \theta_0/2, \\ 0, & \dfrac{\theta_0}{2} < |\theta| \leqslant \pi. \end{cases} \tag{3}$$

Upon leaving the volume of the FPR, the particles are drawn into the processes of drift and diffusion in the corona and gradually escape into interplanetary space.[12] The corresponding transport equation has the form

$$\frac{\partial N}{\partial t} = \frac{1}{r_b^2 \sin\theta}\frac{\partial}{\partial\theta}\left(\varkappa_\theta \sin\theta \frac{\partial N}{\partial\theta}\right) - \frac{V_d}{r_b}\frac{\partial N}{\partial\theta} - \frac{N}{\tau_e}, \tag{4}$$

where κ_θ is the azimuthal diffusion coefficient $V_d \sim (v^2/c^2)/\sqrt{1 - v^2/c^2}$ is the velocity of centrifugal drift across magnetic field lines in the corona,[13] τ_e is the characteristic time of escape of particles from the corona, and r_b is the radial distance from the center of the sun where azimuthal transport begins.

Equation (4) was solved earlier in spherical coordinates by a numerical method.[5] In Refs. 6 and 7 it was shown that, by virtue of the presumed isotropy of dispersion of the particles, the problem can be reduced to the one-dimensional equation

$$\frac{\partial N}{\partial t} = -V_c\frac{\partial N}{\partial x} \tag{5}$$

which, for the FPR, has the solution

$$N(x, t) = \frac{N_a}{x_0}\,\delta(x - x_f - V_c t). \tag{6}$$

Then the initial condition for particle propagation outside the FPR has the form

$$N(x, 0) = \begin{cases} N_a/x_0, & -x_0/2 \leqslant x \leqslant x_0/2 \\ 0, & |x| > \pm x_0/2, \end{cases} \tag{7}$$

while the transport equation (4) can be written as

$$\frac{\partial N}{\partial t} = \varkappa_l \frac{\partial^2 N}{\partial x^2} - V_d\frac{\partial N}{\partial x} - \frac{N}{\tau_e}, \tag{8}$$

where x_0 and x_f are the linear sizes of the FPR and the flare, respectively, κ_ℓ is the transverse diffusion coefficient, and N_a is the energy spectrum of SCR in the source. Under the initial condition (7), Eq. (8) has the analytic solution

$$\begin{aligned} N(x, t) = {} & 2.5 N_a \exp\left[-\frac{t}{\tau_e} - \frac{(x-V_d t)^2 + (x_0/2)^2}{8\varkappa_l t}\right] \\ & \times \left\{\exp\left[\frac{(x-V_d t)(x_0/2)}{4\varkappa_l t} + \frac{(x-V_d t - x_0/2)^2}{8\varkappa_l t}\right]\right. \\ & \times \operatorname{erf}\left(\frac{x - V_d t - x_0/2}{\sqrt{4\varkappa_l t}}\right) - \exp\left[-\frac{(x-V_d t)(x_0/2)}{4\varkappa_l t}\right. \\ & \left.\left. + \frac{(x - V_d t + x_0/2)^2}{8\varkappa_l t}\right]\operatorname{erf}\left(\frac{x - V_d t + x_0/2}{\sqrt{4\varkappa_l t}}\right)\right\}. \end{aligned} \tag{9}$$

It is interesting to note that this solution does not depend on the transport velocity V_c inside the FPR or the size x_f of the source. Estimates[5-7] showed that the model is also insensitive to variations in the rate τ_e^{-1} of particle emission in the range of 3600-36,000 sec^{-1}. From considerations of mathematical simplicity, we did not allow in Eqs. (5)-(8) for adiabatic and collisional losses of particle energy, as well as effects of corotation and the influence of sectoral boundaries between unipolar magnetic regions. Here we are not concerned with the mechanism of opening of the magnetic trap in the model of Refs. 11 and 14, or with the properties of SCR drift and diffusion in the corona (see Refs. 4 and 7 for more detail). Principal attention is concentrated below on calculations of the azimuthal distribution, time profiles, and variations of the SCR spectrum in the corona.

In all the calculations by Eq. (9) we tied in our results to the center of the FPR (i.e., to the position x_f of the flare) in such a way that the relation $x_i = x - x_f$ was satisfied. In doing this, following the model of a magnetic bottle,[11, 14] we introduced the assumption that the FPR has an angular width of $\sim 80^\circ$ at the time of opening of the field lines at an altitude of about 0.9 $r_\odot$ above the photosphere ($r_\odot$ is the solar radius). The drift velocity was chosen, in accordance with observational data (property 4) and theoretical estimates,[13] in the range of $V_d = (60\text{-}250)\beta^2/\sqrt{1-\beta^2}$ km·sec^{-1}, depending on how early the intensity maximum t_m came on the basis of observations at the earth (here $\beta = v/c$, where c is the speed of light). The conversion from angular to linear coordinates was made from the formula $\theta^\circ = (x/1.9r_\odot)57^\circ.2958$; the diffusion coefficient was determined, with allowance for the results of other investigators (see the review of Ref. 7), from the relation $\kappa_\ell = 6.7\cdot 10^6$ v·cm^2·sec^{-1}, while the rate of escap of particles from the corona was taken as τ_e^{-1} = 3600 sec^{-1}.

In addition, we used the fundamentally important assumption that a particle flux with $\varepsilon_c \lesssim 100$ MeV observed at the earth is emitted from the corona mainly at the solar longitude $\theta_\delta \approx 60^\circ$W of the connection between the earth and the sun. At the level of the corona, this flux corresponds to the point $x_c = x(60^\circ \mathrm{W}) - x_f$, while the time of emission from the corona is determined by the relation

$$t_e = \begin{cases} 0, & |x_c| \leqslant x_0/2 \\ |x_c|/|V_d|, & |x_c| > x_0/2. \end{cases} \tag{10}$$

In a different formulation, the assumption adopted above means that the overwhelming majority of the $N(\varepsilon_c)$ spectra from the catalog Ref. 8 (with the exception of those determined from data on flare γ-ray emission) pertain to the solar longitude $\sim 60^\circ$W (emission spectrum). Equating Eq. (9) to the emission spectra, we obtain a formula for determining the energy spectra of the source,

$$N_a(\varepsilon_c) = N(\varepsilon_c)/2{,}5f[x_c,\ t_e,\ V_d(\varepsilon_c),\ \varkappa_l(\varepsilon_c), x_0], \tag{11}$$

where the form of the function f is obvious. In the calculations this function was normalized, $f \leq 1$, while the maximum of Eq. (9) corresponded to the values $t_m = x/V_d$ and $x_c = V_d t$.

4. DATA ON SCR SPECTRA NEAR THE SUN

Up to now, quantitative information has been obtained by various methods on the spectra of emitted particles (protons) for 62 SPE over the period of 1956-1981 (Ref. 8). The spectral characteristics given in the catalog Ref. 8 correspond to one of the following approximations of the differential spectrum:

$$\begin{gathered} D(\varepsilon_c) = D_0 \varepsilon_c^{-\gamma_\varepsilon}, \\ D(R) = D_0 R^{-\gamma_R}, \\ D(R) = D_0 \exp(-R/R_0), \end{gathered} \tag{12}$$

where R is the magnetic hardness of the particles (GV), R_0 is the characteristic hardness of the exponential spectrum (GV); γ_ε and γ_R are the exponents of the spectra in energy and hardness, and D_0 is the number of particles per unit interval of ε_c or R. Besides the usual spectral characteristics appearing in (12), the catalog Ref. 8 also contains estimates of the maximum hardness R_m of the accelerated particles in the source, the coordinates of the flares, and a description of the methods of determining the SCR spectra near the sun.

Unfortunately, the data of the catalog Ref. 8 are uneven, fragmentary, and insufficiently precise, and for certain events the estimates of different authors do not agree with each other. The values of D_0 in the catalog have a methodological uncertainty of the order of two to three, the value of R_0 is determined to within $\lesssim 30\%$, while the error in the exponents of the power-law spectrum is $\Delta\gamma = \pm(0.3\text{-}0.5)$, as a rule. The errors introduced by the imperfection of the models of SCR propagation in interplanetary space are not included here. With no allowance for the asphericity of the region of diffusion (anisoptropy, SCR propagation in a narrow cone, etc.), for example, the estimate of the number $N(>\varepsilon_c)$ of emitted particles can be overstated at least fourfold. And there are other causes for uncertainties in the values of $N(>\varepsilon_c)$ reaching one to two orders of magnitude.[15]

The lack of clarity in questions of the duration of acceleration and emission, the inadequacy of the propagation models, and the difficulties in matching the spectra obtained by different methods and in different energy ranges – all these taken together create considerable uncertainties in the spectral data of Ref. 8. At the same time, it can be shown that the form of the SCR spectra near the sun has peculiarities going beyond the limits of the existing uncertainties.[4, 8] Moreover, the data of the catalog Ref. 8 open up interesting possibilities for the construction of quantitative models of acceleration,[2, 8] estimating and interpreting the values of R_m (Ref. 8), investigating the properties of coronal propagation, and reconstructing the true SCR spectrum in the source.[9]

For the correct interpretation of the data of the catalog Ref. 8, it is important to indicate the peculiarities and limits of applicability of the methods used to reconstruct the spectra near the sun. At present there are three main methods: 1) extrapolation of the observed time profile $I(r_\delta, t)$ of the intensity back to the time of emission $t_0 = 0$ using one or another variant of the diffusional model of Ref. 4; 2) solution of the inverse problem of SCR propagation on the basis of an integral equation with a Green's function of a given type[16]; 3) reconstruction of the parameters of the spectrum in the source from the ratio of the flux of γ-ray quanta to the flux of flare neutrons (see, e.g., Ref. 3, as well as the references in Ref. 8). In certain cases, one uses the ordinary diffusional approximation of the time dependence (i.e., the direct problem of SCR propagation is solved by the method of successive approximations) or a complete transport equation with allowance for adiabatic deceleration and other nondiffusional effects (e.g., transport of accelerated particles in a magnetic trap).

In contrast to the first two methods, the third method is not connected with the use of propagation models and rests entirely on data of the recording

TABLE I SCR Spectra at the Coronal Level and in the Source

Parameters of the flare					Emission spectrum		Spectrum of source	
No.	Date of flare	Flare coordinates	Emission time, UT	Energy range, MeV	D_0 , MeV^{-1}	γ_ε	D_0 , MeV^{-1}	γ_ε
1	22.VIII.1958	18N 10W	16.06	14–130	$3{,}27\cdot10^{36}$	0,90	$1.72\cdot10^{45}$	6.20
2	03.IX.1960	18N 88E	02.29	10–410	$1{,}84\cdot10^{36}$	1.92	$2.28\cdot10^{41}$	3,92
3	28.IX.1961	13N 29E	23.09	14–555	$7{,}89\cdot10^{38}$	3.02	$1.64\cdot10^{43}$	4.63
4	28.I.1967	? 150W	08.24	75–410	$5.2\cdot10^{34}$	1.25	$3.81\cdot10^{36}$	1,82
5	29.IX.1968	13N 13W	10.39	10–190	$1{,}04\cdot10^{34}$	1,5	$1{,}63\cdot10^{40}$	4.20
6	24.I.1969	20N 08W	09.49	10–60	$5.24\cdot10^{35}$	3,1	$4{,}67\cdot10^{43}$	7,20
7	25.IX.1969	13N 15W	09.08	10–60	$1.28\cdot10^{35}$	3,15	$1{,}14\cdot10^{43}$	7.25
8	01.IX.1971	12S 130W	23.26	10–60	$1.43\cdot10^{38}$	2.25	$2{,}81\cdot10^{46}$	6.62
9	28.V.1972	09N 30E	16.44	30–80	$1.09\cdot10^{37}$	2.60	$4.17\cdot10^{41}$	4,60
10	04.VIII.1972	14N 08E	09.51	10–60	$2.00\cdot10^{37}$	7.5	$2{,}03\cdot10^{36}$	2,90
11	09.XI.1979	12S 02W	04.53	30–100	$6.14\cdot10^{32}$	5.24	$4.68\cdot10^{35}$	3,00
12	06.XI1980	12S 74E	09.44	10–60	$9.91\cdot10^{35}$	7,2	$6.36\cdot10^{34}$	2,60

of flare γ-ray quanta (since August 1972) and neutrons (since June 1980). From the relation between the intensities of different γ-ray lines (2.2, 4.4, 6.1 MeV) one can estimate the values of γ_ε and $N(>\varepsilon_c)$ in the region of $\varepsilon_c \lesssim 50$ MeV, while the ratio of the flux of γ-ray quanta with an energy of > 30 MeV to the flux of neutrons with an energy of > 20 MeV one can estimate the same parameters for protons with $\varepsilon_c > 50$ MeV (Refs. 17-19). The first and second methods are suitable in a rather broad region of energies, where one or another variant of the diffusional model operates. The third method is applicable mainly for reconstructing the spectrum of accelerated particles in the range of 10-100 MeV, in which case the reconstructed spectrum is evidently closest to the spectrum of the source. The spectrum can be extended to energies $\lesssim$ 1000 MeV using data on high-energy flare neutrons.

The relative effectiveness of the different methods can be illustrated on the example of the SPE of August 4, 1972. From data on γ-ray lines the authors of Ref. 17 obtained the estimate $N(>30\text{ MeV}) \approx 1.6\cdot10^{33}$, while the authors of Ref. 18 obtained $N(>10\text{ MeV}) \approx 1.35\cdot10^{34}$. These values are consistent with each other and correspond to $\gamma_\varepsilon \approx 2.9$. On the other hand, the authors of Ref. 19 obtained the estimates $N(>30\text{ MeV}) = 6\cdot10^{35}\text{-}10^{36}$, $(1\text{-}2)\cdot10^{33}$, $2\cdot10^{32}\text{-}2\cdot10^{33}$, and $\sim10^{34}$ using the ordinary diffusional model, the models of thick and thin targets (in γ-ray lines), and the complete transport equation, respectively. The use of the diffusional model is hardly justified in this case, however, since the situation in the interplanetary medium on August 4, 1972, was exceptionally complicated.

Besides these uncertainties, the catalog of Ref. 8 contains contradictions and omissions in the estimates of the spectral parameters obtained by different investigators. Therefore, 31 out of the 62 SPE proved suitable for the analysis of effects of coronal propagation within the framework of the model of Refs. 5-7. For simplicity and convenience of comparison, all the spectra near the sun that were used were reduced to power-law functions with respect to ε_c.

5. EVOLUTION OF SCR CHARACTERISTICS IN THE CORONA

In 12 cases out of the 31 events analyzed, the point x_c lay outside the limits of the FPR. For these 12 SPE we calculated, using Eqs. (9)-(11), the SCR spectra in the source (Table I), the azimuthal distributions of particles of different energies for different times, and the time profiles of particles of different energies at different solar longitudes.

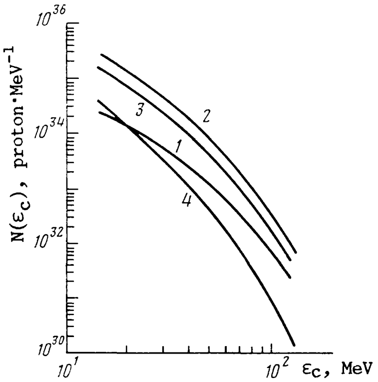

FIG. 1. Proton energy spectra for the SPE of August 22, 1958: 1) observed spectrum[8] near the sun (in the corona); 2) demodulated spectrum of the source (θ_f = 10°W); 3) and 4) expected (calculated) spectra at solar longitudes of 60 and 110°W, respectively.

Similar calculations were made for some of the remaining 19 events, in which the FPR contained the point x_c (for the SPE of February 23, 1956, in particular). We used Eq. (6) to calculate the SCR characteristics inside the FPR.

The results of calculations of the spectrum for the SPE of August 22, 1958, are given in Fig. 1 as an example. From Table I and Fig. 1 it is seen, in particular, that the energy spectra become flatter (harder) at the coronal level than the spectra of the source, as a rule. For the last three cases, Nos. 10-12, the spectra of the source were determined directly from data on the γ-ray emission of the flares, which made it possible to estimate D_0 and γ_ε for the emission spectrum ($\theta_\delta \approx 60°$ W) using Eq. (9). From Table I it is seen that in these three cases the spectra at the coronal level prove to be considerably softer than the spectra in the source. This may indicate errors in the estimates of D_0 and γ_ε from the data on γ-ray emission.

After determining the spectrum $N_a(\varepsilon_c)$ of the source, we constructed time profiles, fixing the solar longitude x_i and the energy ε_i in Eq. (9) and varying the time $t - t_{on}$ relative to the time t_{on}, where $t_{on} = (|x_i|/V_d) - x_0/2$ is the time of the onset of arrival of particles at the given point x_i (i.e., the time $t = t_{on}$ was taken as the onset of the rise). Time profiles for the SPE of August 22, 1958, were calculated for ε_c = 15, 60, and 130 MeV and for several values of θ outside and inside the FPR. On the example of the calculated data for ε_c = 60 MeV (Fig. 2), it is seen that outside the FPR the profiles display a characteristic diffusional form, whereas inside the FPR they have the form of rapidly decaying curves.

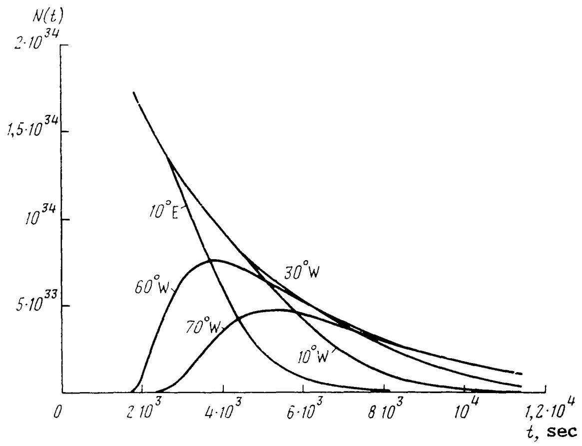

FIG. 2. Calculated time profiles of the flux of protons with ε_c = 60 MeV for the SPE of August 22, 1958, at different solar longitudes (numbers by curves).

In Fig. 3 we show the dynamics (evolution) of the time variation of particles with ε_c = 130 MeV as a function of solar longitude relative to the position of the top of the FPR. Since the time variation is equivalent to variation of the distance to the FPR, for a given value θ, any other value θ' (such that $\theta_f < \theta < \theta$) can be treated as the result of time evolution relative to the time of liberation of the particles from the FPR. Actually, the time profiles for $\theta = \theta_f \pm 40°$ originate at t = 0. Outside the FPR the onset of the rise is delayed in proportion to the distance to the site of the flare in accordance with the observational data.

One more characteristic feature is displayed in the behavior of the time profiles: an east-west asymmetry. Thus, on the example of the profiles for particles with ε_c = 15 MeV for the event of August 22, 1958, it can be shown[9] that at an angular distance of ∿ 50° to the east of the flare one observes ∿ 100 times fewer particles than at the same distance to the west of the flare, while at a distance of ~60° to the east the particle flux decreases to a negligible level in comparison with the western side.

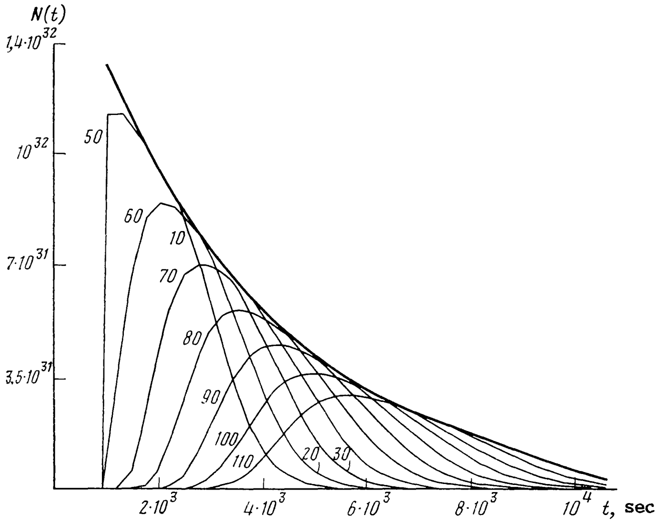

FIG. 3. Evolution of the time dependence of protons with ε_c = 130 MeV as a function of solar longitude (calculation for the SPE of August 22, 1958). Numbers by the curves denote the solar longitude θ °W.

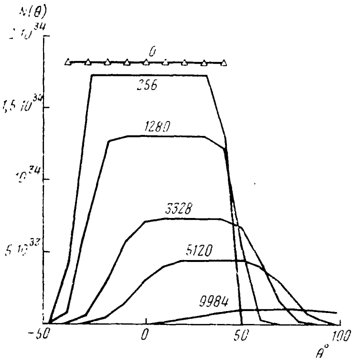

FIG. 4. Azimuthal distribution of protons with ε_c = 60 MeV for several times (calculation for the SPE of August 22, 1958). Time in seconds (numbers by the curves).

To construct the azimuthal particle distributions we fixed the values of ε_i and t and used (9) to estimate the values of N for $x_i \le \pm 180°$, taking the position of the flare as the origin of coordinates. For the event of August 22, 1958, the distributions were calculated for ε_c = 15, 60, and 130 MeV. For example, in Fig. 4 we show the azimuthal distribution of particles with ε_c = 60 MeV for several times. By comparing the results for three different energies, one can see[9] that the observed east-west asymmetry of the distribution is confirmed by our calculations: The higher the particle energy, the more clearly is the asymmetry effect displayed. This corresponds theoretically to the incorporation of particle drift into the model of coronal transport.

It is interesting to estimate the spectrum of the source under the assumption that the flare has a finite angular size. In Fig. 5 we give the results of calculations of the spectrum of the source from Eq. (6) for the SPE of August 22, 1958, with $\delta\theta_f$ = 8°, as well as the spectrum at the top of the FPE at t = 0 (at the time it opens up), in units of particle·MeV^{-1}·cm^{-1}. It is seen that under such an assumption, the energy spectrum of the source has a tendency to take a power-law form in the energy range under consideration.

6. CONCLUSION

Our proposed approach does not yet include many physical aspects of coronal transport and the space-time characteristics of the FPR, and the results obtained obviously are model-dependent. Therefore, the model under consideration cannot pretend to be an exhaustive explanation of all the features of the coronal propagation of SCR. At the same time, certain essential features of this process

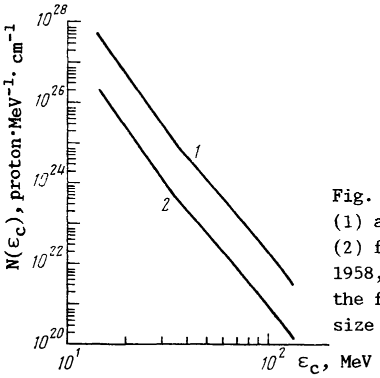

Fig. 5. Spectrum of the source (1) and spectrum in the corona (2) for the SPE of August 22, 1958, under the assumption that the flare has a finite angular size $\Delta\theta_f$ = 8°

are described fully satisfactorily by the model, despite its simplicity. We note the following main results.

1. A clear picture of the evolution of the spectrum of SCR as they propagate in the corona (both inside and outside the FPR) is shown. The differences between the spectra in the FPR and the SPR at long times and considerable distances from the falre are especially pronounced.

2. The emission spectra ($\theta_{♁} \approx 60°$ W) are flatter (harder) than those in the source. This effect is displayed more strongly in the low-energy region.

3. The time profiles and azimuthal distributions of SCR display an east-west asymmetry. This effect influences the form of the spectrum, and its variations are more pronounced as the particles move from west to east. The differences in fluxes can reach 100-fold at equal solar-longitude distances relative to the flare.

4. If the FPR contains the solar longitude $\theta_{♁}$ of connection between the earth and the sun, then the observed spectrum (emission spectrum) and the demodulated spectrum (spectrum of the source) practically coincide.

It is interesting to analyze out results with allowance for the observed effcts and model predictions summarized in the review Ref. 7. We are convinced that the approach developed here must be taken into account in the theory of the acceleration of solar particles and in the construction of a model of a solar flare, particularly in estimates of the energetics of SCR and the energetics of a flare as a whole, and in calculations of fluxes of flare neutrons and various kinds of nonthermal electromagnetic radiation.

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