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The Spectrum of Accelerated Particles in Solar Proton Events with a Rapid Component

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A number of solar proton events are analyzed in which two components of relativistic protons (an anisotropic rapid one (RC) and an isotropic slow one (SC)) were observed. The spectra of RC emission are reconstructed for the events of February 23, 1956, December 7, 1982, and February 16, 1984. It is shown that one can match the obtained spectra with a model of a source located in the region of reconnection of the lines of force of a magnetic bay and the neighboring magnetic arcade (SK).* Acceleration of particles is accomplished by pulsed electric fields arising upon the rupture of the current layer in the reconnection region. The proposed model permits, in particular, satisfactorily describing the position of the source, the temporal profile, the spectrum, and the anisotropy of the solar cosmic rays (SCRs) in the event of February 16, 1984.

INTRODUCTION

The high accuracy of recording of ground increases of solar cosmic rays (SCRs) with the help of neutron supermonitors permits tracing, with an accuracy of up to 1 min, the development of a solar proton event (SPE) in the region of rigid particles $R \gtrsim 1$ GV. It has proven possible to reveal interesting peculiarities of the SCR distribution function at the earth and near the sun. For example, indications have been obtained for some events [1-3] about the possible existence of two proton components, an anisotropic rapid one (RC) and an isotropic slow one (SC). The emission of the rapid component starts ~8 min after the start of a Type II radio flare, and this time amounts to ~30 min for the slow component.

By our estimates, one can relegate the cases of ground increases of February 23, 1956, May 4, 1960, July 20, 1961, November 18, 1968, May 7, 1978, December 7, 1982, February 16, 1984, and possibly November 19, 1949, to events with a rapid component (Class I). Class I events are characterized by a short duration, a rigid spectrum, and a strong anisotropy, especially up to the maximum and near it. Class II events, as a rule, have a "diffuse" temporal profile of the intensity $I(t)$ and are distinguished by weak anisotropy after the maximum (the event of October 12, 1981, can serve as a typical example). In some cases (for example, February 12, 1956, and December 7, 1982), it has proven possible to distinguish both components, but evidently only the rapid component was recorded on February 16, 1984 [1-3].

An attempt is made below to model the properties of the source of the rapid component on the basis of data of SCR observations and calculations of the generation spectrum upon reconnection of the lines of force of two magnetic loops or bottles high in the corona.

PROPERTIES OF THE RAPID COMPONENT AND A MODEL OF THE SOURCE

Figure 1, in which temporal profiles of the intensity for the event of December 7, 1982, are plotted from data of neutron monitors, demonstrates the existence of two components of relativistic SCRs. According to [4], the monitor at the Kergelen station (*1*) recorded particles from the direction along the anisotropy axis, and the monitor at the Deep River station (*2*), from the opposite direction. One can ascribe the region of profile *1* (crosshatched) to the rapid (anisotropic) component [2, 3]. Calculating the difference in areas occupied by profiles *1* and *2*, we obtain that

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*Ed. Note: It is believed authors are referring to solar prominence arch, which connects via solar wind to the magnetosphere.

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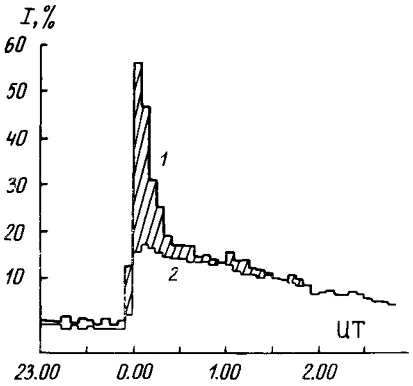

Fig. 1. Temporal profiles of the intensity in the event of December 7-8, 1982, according to data of the (*1*) Kergelen and (*2*) Deep River neutron monitors. The crosshatched difference between these profiles corresponds to the rapid component.

the rapid component amounts to about 23% of the integrated flux of relativistic particles in the event in question. All Class I events are related to solar flares observed near the western limb of the sun. The event of February 16, 1984, for which no source (flare) was found on the visible disk of the sun (emissions in the H_α line and in the soft X-ray region 0.1-0.8 nm were not present), and the heliolongitude expected from various estimates varies within the limits $\theta_f \leq 95°W - \sim 130°W$.

A magnetic bottle [5] upon its expansion is evidently [2, 3] a possible source of the slow component, and the rapid component is presumably generated in the region of reconnection of magnetic loops upon the stimulating action of a coronal shock wave or an expanding magnetic bottle.

An attempt is made below to model the properties of the rapid component on the basis of the data of SCR observations and calculations of the generation spectrum upon the reconnection of the lines of force of two magnetic loops or bottles high in the corona.

The physical model of the source should adequately reflect the characteristic properties of the rapid component [1-3].

1. Flares after which the rapid component was recorded have a tendency to be located outside the optimal heliolongitudinal interval $\theta_{\oplus} \approx 50-60°W$, where $\theta_{\oplus}$ is the heliolongitude of the connection of the earth to the sun by means of the appropriate line of force of the IMF.
2. The emission of the rapid component starts already prior to the onset of the opening of the magnetic bottle.
3. The growth time and the decay time of the intensity in events with a rapid component are small, which indicates free escape of particles to open lines of force of the IMF and propagation in interplanetary space almost without scattering.
4. The emission of the rapid component is of an anisotropic nature: the number of protons with pitch angles $\theta_0 \sim \pi/2$ is negligibly small at the time of emission.

Increases of the SCR flux in events with a rapid component are of an impulse nature and have an anomalously rigid spectrum, which may indicate the specific mechanism of rapid acceleration.

We shall assume that a flare properly develops at coronal altitudes $h \approx (0.07-0.14)R_\odot$ ($R_\odot$ is the sun's radius) in accordance with the scenario of [5]. A flare magnetic bottle upon expansion comes into contact with the adjacent magnetic loop at altitudes $h \approx (0.5-1)R_\odot$, where a current layer is formed in the course of magnetic reconnection. Acceleration of particles is accomplished by the pulsed electric fields which arise upon the rupture of the current layer. The evolution of the proposed magnetic configuration, which we constructed in accordance with the results of [6-10], is shown in Fig. 2. As follows from the data on coronal transients [8], the plasma density in the upper part of the magnetic bottle can be several times higher than in the surrounding corona (for altitudes $\sim 0.5-1R_\odot$, for example, $n \sim 10^6-10^7$ cm^{-3}), and the magnitude of the magnetic field B amounts to a few units or tens of gauss. As has been shown [9, 10], the appearance of an additional flux of accelerated particles, whose maximum should be observed up to the maximum of strictly flare particles, is possible. To achieve the best agreement between the observed and expected spectra of the rapid component, in the following calculations the parameters n and B were selected within the limits indicated above, and the length L of the current layer was taken as $\sim 0.1R_\odot$.

GENERATION SPECTRUM OF THE RAPID COMPONENT

To obtain the power spectrum of particles accelerated in the electric fields in the reconnection region (Fig. 2), the authors of [11] considered the motion of particles in the configuration $B = (B_x, B_y, 0)$, where the particle's trajectory is determined by the electromagnetic force $\mathbf{F} = e(\mathbf{E} + \frac{1}{c}[\mathbf{vB}])$. Here v and e are the velocity and change of the particle, c is the speed of light, and $\mathbf{E} = \frac{1}{c}[\mathbf{uB}]$ is the electric field which arises in the current layer mainly due to spatial variations of $\mathbf{B}$ when the lines of force diffuse within the layer with velocity $\mathbf{u}$. At times $t = 0$ (prior to the onset of diffusion), the particles have the initial coordinates $(x_0, y_0, 0)$. As follows from the calculations of [11], the final energy distribution of the particles depends on the random scatter of their initial coordinates in the acceleration region. In the configuration under discussion, the differential power spectrum can be represented in the form

$$N(\epsilon)\, d\epsilon\, dz = J_0 \,| dx_0/d\epsilon |\, d\epsilon\, dz, \qquad (1)$$

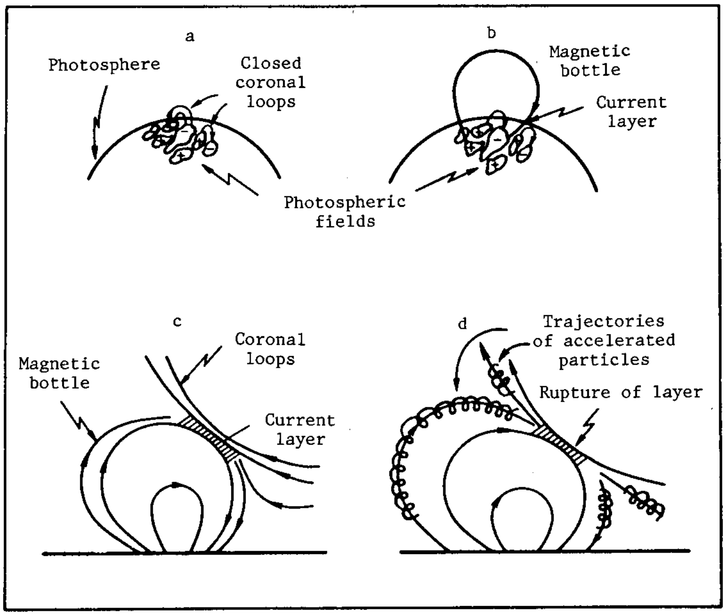

Fig. 2. Model of the source of the rapid component of SCR: a) active region with complex magnetic structure; b) formation of a magnetic bottle and start of its interaction with the adjacent solar magnetic arch; c) formation of a current layer; d) acceleration of particles.

(N is in $\mathrm{cm}^{-1}\cdot\mathrm{s}^{-1}\cdot\mathrm{eV}^{-1}$), where J_0 is the local particle flux on the boundary of the acceleration region and x_0 is the initial position of the particle, which is determined by the thickness of the diffusion region (layer) δ and the characteristic energy ε_*:

$$x_0 = 1{,}36\delta \exp[-1{,}12(\epsilon/\epsilon_*)^{3/4}]. \qquad (2)$$

Combining (1) and (2), we obtain the final computational formula for the generation spectrum [11]:

$$N_\odot(\epsilon) = N_0(\epsilon/\epsilon_*)^{-1/4}\exp[-1.12(\epsilon/\epsilon_*)^{3/4}], \qquad (3)$$

where N_0 has the dimensionality $\mathrm{proton}\cdot\mathrm{MeV}^{-1}$, and the energy values are expressed in MeV. The characteristic energy ε_* is related to the parameters of the source as follows:

$$\epsilon_* = (eLBum_p^{1/2}/2c) = 8.236 \cdot 10^{-3}(B^3L/n)^{2/3}, \qquad (4)$$

where the reconnection velocity u (the diffusion velocity of the lines of force within the current layer) is related to the Alfvén velocity v_A by the relationship: $u = 0.057\ v_A$ [6]. The constant N_0 in the spectrum (1) is equal to $N_0 = AL^2/u\epsilon_*$, where $A = k\delta nu$, $k = 1.1436$, the thickness of the current layer $\delta = c^2/(4\pi\sigma u)$, the anomalous conductivity $\sigma = 4.49\cdot10^2\cdot n^{1/2}\cdot c^{-1}$ (in cgs units), and the volume of the acceleration region $V = \delta L^2$. After substitution of all the factors and constants into the expression for N_0, we finally obtain:

$$N_0 = 1.468 \cdot 10^7(nL^2/B\epsilon_*) \qquad (5)$$

(N_0 is in units of $\mathrm{proton}\cdot\mathrm{MeV}^{-1}$).

The generation spectra were calculated using formulas (3)-(5) for three events, February 23, 1956, December 7, 1982, and February 16, 1984.

As should have been expected, the calculated generation spectra (3) differ from the model of formation of SCR spectra upon magnetic reconnection [12, 13] in an important characteristic—the smooth variation of the slope with a gradual flattening (stiffening) in the low-energy region. The corresponding SCR emission spectra reconstructed using observations obtained on the earth's surface were used for comparison. It is assumed that the reconstructed spectra obtained by the procedure of [14] pertain to the optimal heliolongitude of emission $\theta_\delta \approx 60°\mathrm{W}$. Unfortunately, the procedure of [14] does not permit distinguishing the rapid and slow components in the emission spectra. However, it proved possible for us, using the peculiarities of behavior of the rapid component at the earth, also to estimate its spectrum at the instant of emission for the three events cited above. The quantitative differences between the generation spectra (3) and the emission spectra of the rapid

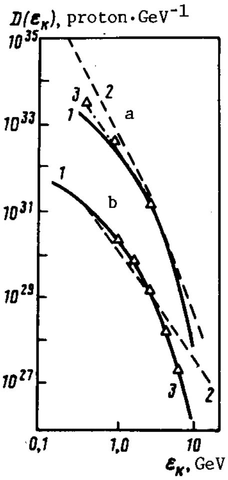

Fig. 3. (*1*) Calculated generation spectrum, (*2*) reconstructed emission spectrum of the total SCR flux, and (*3*) the emission spectrum of the rapid component (triangles) for the events of (a) February 23, 1956, and (b) February 16, 1984.

component and the total SCR flux are discussed below, separately for each event.

The event of February 23, 1956. The generation spectrum (curve *1* in Fig. 3a) is obtained with the following source parameters: B = 30 G, $2 \cdot 10^7$ cm^{-3}, and $L = 10^{10}$ cm. The emission spectrum w, which was reconstructed in [15] in the form $D_{\odot}(R) = 10^{34} R^{-5.4 \pm 0.2}$ GV^{-1} for the interval R = 1-15 GV, evidently contains the sum of the rapid and slow components. We used the spectrum of the direct (with the symbol "d") SCR flux, obtained in [16] in the form $D^{d}_{\oplus}(R) \sim R^{-3.4}$ for the interval R = 1.3-4 GV from the difference of the growth amplitudes in the shock zones and at opposite sites of the earth, to estimate the emission spectrum of the rapid component. One can represent the spectrum in absolute units [16] in the form $D^{d}_{\oplus}(R) = 2 \cdot 10^3 R^{-3.4 \pm 0.2}$ cm^2·s^{-1}·GV^{-1}. Neglecting scattering of relativistic protons in the space between the sun and the earth, one can estimate the emission spectrum of the rapid component from the formula

$$D_{\odot}^{\mathrm{RC}}(R) = (2 \div 4)\pi r_{\oplus}^2 \Delta t D_{\oplus}^{d}(R), \qquad (6)$$

where $r_{\oplus}$ is the radius of the terrestrial orbit and Δt is the recording time of the direct flux. If one assumes the source to be instantaneous and highly anisotropic (zero pitch angles of emission), and scattering in the interplanetary medium to be negligibly small, then the particle distribution function at the earth will be of the form $F_d \sim \delta(\tau)$ [32], where $\tau = t - (z - z_0)/v$, the coordinate z is figured along a line of force of the IMF, and z_0 is the coordinate of the source. This approximation corresponds to the case in which all particles having velocity v arrive at the observation point in a time $t = (z - z_0)/v$. For relativistic particles $v \approx c$, the scatter in the energies does not result in a scatter in the arrival times. If one takes account of the fact that under typical conditions in the interplanetary medium the length of a line of force, $z_{\oplus} \approx 1.2$ AU, then we obtain $\Delta t \approx 600$ s = 10 min. It now follows from (6) that $D^{\mathrm{RC}}_{\odot}(R) = (1.11\text{-}2.22) \cdot 10^{33} R^{-3.4 \pm 0.2}$ GV^{-1} (spectrum 3 in Fig. 3a). The absolute values of the particle number for spectra *2* and *3* have a systematic indeterminacy ≥2 [15].

It is interesting to note that spectrum *3* lies below spectrum *2*, merging with it at an energy ~3 GeV ($R \approx 4$ GV). This fact does not contradict the result of [11], in which it has been shown that the number of accelerated particles is relatively small in the acceleration process at high latitudes in the corona upon the reconnection of magnetic fields with the topology of Fig. 2, and their maximum energy $\epsilon_{\max} = eEL$ (E is the magnitude of the electromagnetic field) reaches values of 1.8-3.7 GeV ($R_{\max} \approx 1.25\text{-}4.5$ GV). We note, however, that the quantity $\varepsilon_{\max}$ depends significantly on the choice of the parameters B, n, and L.

Actually, taking account of the fact that $E = (u/c)B$, where $u \lesssim 0.057 V_A$ [6], we obtain $\epsilon_{\max} \sim (1/c)B^2 n^{-0.5} L$. The quantity $\varepsilon_{\max}$ for the event of February 23, 1956, amounts to ~250 GeV for a source with the parameter values indicated above the magnetic topology of Fig. 2. As a result of the steeply falling spectrum, the intensity of particles with such an energy should be small. Actually, a maximum energy of solar particles ~20 GeV was recorded by the ground detectors which existed at the time.

The event of December 7, 1982. We used the following data for the analysis of this event: the generation spectrum in the form $D_{\odot}(\epsilon_k) = 2.23 \cdot 10^{37} \epsilon_k^{-3.7}$ MeV^{-1} for protons with $\varepsilon_k > 30$ MeV calculated from γ radiation observations [17]; the spectrum of the direct SCR flux at the earth in the form $D^{d}_{\oplus} = D_0 R^{-\gamma_R}$, where $\gamma_R = 2.8 \pm 0.1$ [18]; the emission spectrum of the total SCR flux reconstructed by the authors of [19] from data of observations at the earth with the help of the procedure of [12]; data on the anisotropy of SCRs at the earth [20]; and the approximation of the rigidity dependence of the integrated multiplicity of generation for the neutron component in the form $m(R) = 5.8 \cdot 10^{-5} R^{2.1}$ for the interval R = 1-10 GV [21].

As has been noted above, it proved possible in the event of December 7, 1982, to distinguish the rapid and slow components. The author of [18] estimated the exponent of the differential spectrum of protons for rigidities in the region $R \geq 1$ GV for the direct SCR flux according to the data of two different neutron detectors of the Sanae (Antarctica) station. The value of D_0 was not determined. We used the method of [16] to calculate it, with account taken of the data on the

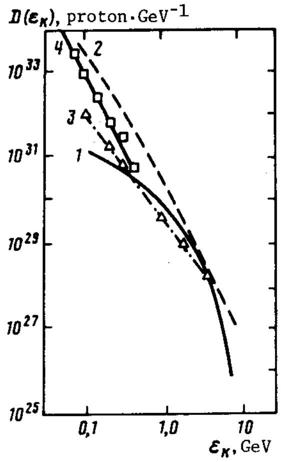

Fig. 4. Spectra for the proton event of December 7, 1982: *1*) calculated generation spectrum; *2*) reconstructed emission spectrum of the total SCR flux; *3*) emission spectrum of the rapid component; and *4*) generation spectrum obtained from data on γ radiation of the flare.

difference of the growth amplitudes and the temporal profiles at the Kergelen and Deep River stations, which have almost identical threshold rigidities ($R_c \approx 1.1$ and 1.07 GV, respectively) but are located at opposite points of the earth [4]. The indicated differences are evident from Fig. 1, in which the temporal profiles of the growth amplitude at the two stations are given. Assuming that at the instant of the maximum (00 h 05 m UT on December 8), the predominantly direct SCR flux was recorded at the Kergelen station and the scattered flux at the Deep River scattered flux at the Deep River station, we obtain the relative growth amplitude of the rapid component: $A_{\mathrm{RC}} = A_{\mathrm{K}} - A_{\mathrm{DR}} = 56\% - 17\% = 39\%$ [18]. The absolute value of the flux of the rapid component is related to its spectrum by the relationship [21]:

$$F_{\mathrm{RC}}\,(>1\ \mathrm{GV}) = \int_{1}^{R_m} D_{\delta}^{\mathrm{d}}(R)\cdot 5.8\cdot 10^{-5} R^{2.1}\,dR, \tag{7}$$

where the procedure of [21] F_{RC} (>1 GV) = $39\%\cdot 10{,}224\cdot 10^{-6}\cdot 7\ \mathrm{cm}^{-2}\cdot\mathrm{s}^{-1} = 2.8\times 10^{-3}\ \mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}$, $D_{\delta}^{\mathrm{d}}(R) = D_0^{\mathrm{d}} R^{-2.8\pm0.1}$, and one can set $R_m \lesssim 10$ GV. It follows from (7) that $D_0^{\mathrm{d}} \approx 1.5\cdot 10^{1}\ \mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}\cdot\mathrm{GV}^{-1}$, so that we obtain with the help of (6) the spectrum of the rapid component at the instant of emission $D_{\odot}^{\mathrm{RC}} = (1.06-2.12)\cdot 10^{31} R^{-2.8\pm0.1}\ \mathrm{GV}^{-1}$. This spectrum (*3*) is shown in Fig. 4 along with the generation spectrum *4* [17] and the emission spectrum *2* of the total SCR flux [19]. The calculated spectrum *1* was obtained on the basis of the relationships (3)-(5) with the following choice of parameters: $B = 20$ G, $n = 2\cdot 10^{6}\ \mathrm{cm}^{-3}$, and $L = 0.2\cdot 10^{10}$ cm.

Spectrum *4* possibly pertains to the slow component and is similar to the emission spectrum of the total flux (2), for which the authors of [17] have independently obtained estimates of the exponent of the energy spectrum of emission: $\gamma_{\odot} = 3.2 \pm 0.7$ for $\varepsilon_p > 60$ MeV and $\gamma_{\odot} = 4.5 \pm 1.5$ for $\varepsilon_p \gtrsim 500$ MeV. We shall assume that the emission spectrum has an exponent $\gamma_{\odot} \approx 3.2$ for energies $\varepsilon_p < 60$ MeV (right up to $\varepsilon_p \gtrsim 10$ MeV). Then according to the data of the Meteor satellite [22], one can obtain the following estimate for protons with $\varepsilon_p > 15$ MeV: $D_{\odot}(\varepsilon_k) = 5{,}4\cdot 10^{37}\,\varepsilon_k^{-3{,}2\pm0{,}7}\ \mathrm{MeV}^{-1}$, which agrees within the limits of accuracy of the procedure with the result of [17] for the very same energy region.

The event of February 16, 1984. The properties of the source, as well as the temporal, angular, and spectral characteristics of this event, have been analyzed in many papers (see [1-3, 10, 18, 20, 23-28] and their references). However, it did not prove possible in these investigations to construct a noncontradictory picture of the event. For example, the velocity of the coronal shock wave included by the authors of [25] to describe the acceleration process turns out to be too large, about 10^{4} km·s^{-1} (on the assumption of a beyond-the-limit position of the flare $\theta_f \approx 130°$W). Moreover, the selected acceleration mechanism does not provide for the formation of a spectrum with a variable slope $D_{\odot}(R) = D_0 R^{-\gamma}\exp(-R/R_0)$, where $\gamma = 4$-5 and $R_0 \gtrsim 5$ GV (the spectrum near the sun was reconstructed in this form by the authors of [26] from the data of observations at the earth in the energy interval $\varepsilon_p = 20$-10^{3} MeV). It is also difficult to match the data of observations of the onsets of a 5.2 GHz microwave flare on the earth (08.58:30 UT) and rigid X-ray emission with energy >25 keV by the ICE spacecraft (at a distance of 0.7 AU from the earth at 08.58:18 UT) and >250 keV (the PVO spacecraft in Venus' orbit at longitude ~106°W at 08.57:30 UT) with a beyond-the-limb position of the source. These data show that the acceleration of the first particles at the sun occurred no earlier than 08.50 UT ± 2 min [27]. This does not contradict the time of onset of the recording of relativistic protons of 09.04:30 ± 1 min on the earth's surface (on the assumption of their propagation in the IMF practically without scattering along the guiding line of force with small pitch angles). On the other hand, the stay time of accelerated particles in the corona turns out to be small and practically identical for protons over a wide range of energies $\varepsilon_p \gtrsim 10$-10^{3} MeV [1-3]. In essence, the only argument in favor of a beyond-the-limb position of the source of observed SCRs is the absence of a flare in the H_{α} line on the visible disk of the sun. A number of proofs in favor of the assumption that the source could be located on the visible disk in the magnetic configuration of Fig. 2 are given below. We shall rely primarily on data on the spectrum and anisotropy of SCRs.

As follows from the analysis of [1-3], only the rapid component of SCRs was evidently recorded near the earth on February 16, 1984. According to the data of two neutron detectors sensitive to different effective energies of primary particles and located at one site (Antarctica, Sanae station, R_c = 0.91 GV), the spectrum of the direct flux had the form $D_{\delta}^{d}(R) = D_0 R^{-2.6 \pm 0.1}$ $cm^{-2} \cdot s^{-1} \cdot GV^{-1}$ at the increase's maximum (09.05-09.10 UT) [18]. A similar comparison of the increase's amplitudes recorded by and unshielded neutron counter and a neutron monitor at the South Pole station, at which the rigidity of the geomagnetic cutoff is R_c = 0.10 GV and the median value of the energy of the recorded solar protons for this event amounted to ~10^3 MeV (1.7 GV) [25], indicates a very rigid spectrum at the start of the event. According to the estimates of [25], the event of January 26, 1984, had the most rigid spectrum among the 10 most prominent events up to 1984. However, the slope of the spectrum was, according to the estimates of [25], somewhat greater than that in [18]; for the very same time interval $D_{\delta}(R) = 9.23 \cdot 10^1 R^{-3.5}$ $cm^{-2} \cdot s^{-1} \cdot GV^{-1}$, which agrees within the limits of accuracy of the procedure (a factor ≳2) with the result of [24] obtained by an independent method. The maximum of the integrated intensity was observed in the interval 09.05-09.20 UT; the spectrum had the form $D_{\delta}(R) = 1.06 \cdot 10^2 R^{-4.45}$ $cm^{-2} \cdot s^{-1} \cdot GV^{-1}$; the spectrum subsequently gradually softened, and in the interval 09.45-10.00 UT, it took the form $D_{\delta}(R) \approx 5 \cdot 10 R^{-5.00}$ [25], which is typical for many events in the late stages.

As the authors of [25] assume, the indeterminacy of the spectral points obtained from the data of the neutron monitors does not exceed a factor of two. Thus, if one assesses the temporal evolution of the spectrum at the earth, the event of February 16, 1984, recalls many other events; however, its time scale is compressed by several times in comparison with other similar events: by a factor of ~5-6 with respect to the SPE of December 7, 1982, and by approximately a factor of 12, in comparison with the event of February 23, 1956. What has been said has also been confirmed by the behavior of the anisotropy [25]. During the first 40 min, the amplitude of the anisotropy was held at a level 1, and in the interval 09.45-10.00 UT, it was lowered to ~0.5. This indicates that in the late stages of the event the measured spectrum of high-energy protons does not have a direct relation to the emission spectrum (the protons were subjected to noticeable scattering by inhomogeneities of the IMF).

We shll use data on the increase's maximum amplitude on the earth's surface (Goose Bay station t_m = 09.05-09.10 UT, R_c = 0.57 GV, median energy of recorded solar protons in this event is ~1300 MeV ($R \approx 2.03$ GV) [25]) to estimate the emission spectrum of the rapid component. According to the estimates of [25], the direction to the source (the anisotropy axis) at 09.07 UT was close to the main cone of asymptotic directions of particle arrival at the Goose Bay station. With this taken into account, we obtain from $D_{\delta} = 1.7 \cdot 10 R^{-2.6 \pm 0.1}$ $cm^{-2} \cdot s^{-1} \cdot GV^{-1}$. When the data of the Sanae station (A_m = 65%, and the angle between the direction of maximum flux and the anisotropy axis is ~30°) is used, the value of D_0 in the obtained spectrum decreases by a factor of ~1.5. Now we shall calculate with the help of formula (6) the most probable emission spectrum of the rapid component $D_{\odot}^{RC}(R) = 6 \cdot 10^{30} \cdot R^{-2.6 \pm 0.1}$ GV^{-1} on the assumption that the particles occupied a solid angle no greater than π near the earth, as a result of the strong anisotropy. This estimate is close to the emission spectrum $D_{\odot}(R) = (5 \pm 2) \cdot 10^{30} R^{-3.3 \pm 1.2}$ GV^{-1}, which was obtained by the authors of [24] by the method of numerical solution of the inverse problem of SCR propagation. It is appropriate to note that the slope of the spectrum at the earth obtained in [24] and [25] for the interval 09.05-09.10 UT agrees, within the limits of the procedure's errors, with the slope of the reconstructed emission spectrum of [24] and does not differ very significantly from the slope of the emission spectrum of the rapid component.

The calculated generation spectrum *1* obtained for B = 20 G, $n = 5 \cdot 10^6$ cm^{-3}, and $L = 0.2 \cdot 10^{10}$ cm, the emission spectrum *2* (dashes of [24], and the emission spectrum of the rapid component *3* (triangles) estimated above are given in Fig. 3b. It is evident that the spectrum of the rapid component practically agrees, within the limits of accuracy of the procedure, with the emission spectrum of [24] and is in satisfactory agreement with the calculated generation spectrum.

THE POSITION AND PROPERTIES OF THE SOURCE OF THE SPE OF FEBRUARY 16, 1984

The direction to the source, whose projection onto the earth's surface had geographic coordinates 6°S, 5°E, was determined for the instant 09.07 UT, with the asymptotic arrival directions of the particles at the Goose Bay station in [25] taken into account. Beyond the confines of the magnetosphere, this corresponded to an angle $\Psi = 40°$ between the radial direction from the sun and the line of force of the IMF. Such a value of the angle seems improbable. Actually, a solar wind velocity $u \approx$ 300 $km \cdot s^{-1}$ was recorded by the ICE spacecraft, which at the instant of the event was located at a distance of 0.07 AU from the earth upstream of the interplanetary plasma and near the nominal line of force connecting the earth to the sun. The active region AR 4408, responsible for the suggested beyond-the-limb flare at heliolongitude $\theta_f \approx 130°$W, was located at heliolatitude $\varphi \approx 12°$S at the instant of the event. According to Allen [30], the angular rotational velocity of the sun (at heliolatitude $\varphi = 12^\circ$) amounts to $\Omega_0 = 2.865 \cdot 10^{-6}$ rad$\cdot$s$^{-1} \approx 14.2^\circ$ day^{-1} (14.3° day^{-1} on the equator). We shall make use of the formula:

$$\Psi = \mathrm{arctg}[(r\Omega_\odot/u)\sin(\pi/2 - \varphi)] \qquad (8)$$

for calculation of Ψ.

At $r = 1 - 0.07 = 0.93$ AU, $\varphi = 12^\circ$ and $u = 300$ km$\cdot$s^{-1}, from which follows $\Psi = 52.5^\circ$. It is also evident from formula (8) that a velocity $u = 476$ km$\cdot$s^{-1} should correspond to a value $\Psi = 40^\circ$.

The sensitivity of formula (8) to the values of r, Ω, and u affects the determination of the source's position, since its heliolongitude depends on the same combination of parameters: $\theta_\odot = \theta_{CM} + r\Omega/u$, where θ_{CM} is the longitude of the central meridian of the sun, which is usually taken as the reference point ($\theta_{CM} = 0^\circ$). For $u = 300$ km$\cdot$s^{-1} and $r = 1$ AU, we obtain $\theta_\odot \approx 82^\circ$W. This denotes that the point of SCR emission on February 16, 1984, was evidently located on the sun's visible disk far from the suggested site of the flare. With the spectral and temporal characteristics of the event taken into account, we have a right to assume that the acceleration occurred on the sun's visible disk, possibly in the magnetic configuration of Fig. 2.

To understand the peculiarities of SCR generation on February 16, 1984, it is necessary to compare the times of emission with the characteristics of particle transport in the IMF. The line of force connecting the sun to the earth is calculated from the formula

$$s = \frac{r(1+\alpha^2 r^2)^{1/2}}{2} + \frac{\ln[\alpha r + (1+\alpha^2 r^2)^{1/2}]}{2\alpha}, \qquad (9)$$

where $\alpha = \Omega\cos\varphi/u$. With $\Omega = 2.865 \cdot 10^{-6}$ s^{-1}, $\varphi = 12^\circ$, $u = 300$ km$\cdot$s^{-1}, and $r = 1$ AU, we obtain $s = 1.282$ AU from (9), which for a particle with energy 1300 MeV and zero initial pitch angle gives flight times from the sun to the earth of $t_s = s/\beta c = 12$ min. According to the estimates of [27], protons with $\varepsilon_p \approx 1300$ MeV were generated on the sun at 08.53:30 ± 1 min and started to arrive at the earth at 09.53 ± 1 min; i.e., the time of their propagation in the IMF agrees to within an accuracy of ±1 min with the value of t_s. For a particle with $\varepsilon_p = 75$ MeV the quantity $t_s = 28.3$ min, which is comparable with the estimate of [27] of their propagation time of 26 ± 2 min. The generation of accelerated particles in the event under discussion occurred, according to the estimates of [27] from data on the recording of rigid (>250 keV) X-ray radiation by the PVO spacecraft, around 08.49 ± 2 min. With the uncertainties of the time estimates given above taken into account, one can, in our opinion, assume that SCR generation on February 16, 1984, occurred in a δ-like, or in any event, very short-lived process. The emission of accelerated particles was evidently facilitated by the appreciable altitude of the source and an outflow to open lines of force of the IMF, and transport in interplanetary space occurred almost without scattering along the lines of force. The latter circumstance has been confirmed by the strong anisotropy and large values of the transport free path $\Lambda > 2$ AU obtained by the authors of [23] for relativistic protons. The pitch angle distribution of such protons at the instant of emission (near the sun) reconstructed by the authors of [35] from observations at the earth has the form of a narrow Gaussian curve $f(\theta) \sim \exp(-\theta^2/\theta_*^2)$ with the characteristic parameter $\theta_* \approx \pi/4.15$. About half of the flux of escaping particles have pitch angles $\theta_0 \leqslant \pi/5$.

DISCUSSION OF THE RESULTS

At least three possible versions of the generation, transport, and emission of SCRs in the February 16, 1984, event (which can be generalized to the rapid component in the general case) follow from the arguments expounded above and the results of other investigations.

1. A flare occurs beyond the limb and generates a shock wave, which is the source of the accelerated particles. When the favorable longitude of connection $\theta_\delta \approx 82^\circ$ is reached by the wave, the accelerated particles depart for the earth along open lines of force. An objection to such a possibility is the fact that the intensity of particles escaping from the bottle and accelerated by the shock wave cannot be very large. Moreover, the observed intensity of the rapid component at the maximum is usually appreciably higher than the intensity of the slow component, which comprises the bulk of the particles (Fig. 1).

2. A flare occurs beyond the limb, particles are accelerated in a pulse phase, and then they are transported in an expanding magnetic bottle. Upon the bottle's breakdown (due to a Rayleigh-Taylor instability [5]), its periphery ($\theta = \theta_f \pm 50^\circ$) can turn out to be near the favorable heliolongitude of connection $\theta_\delta = 82^\circ$W, and the particles will be able to reach the earth along open lines of force. In this case, however, it is difficult to explain the anomalously rigid spectrum of the particles in the February 16, 1984, event [19], since particles of the slow component, whose source is a magnetic bottle [2, 3], are usually characterized by a comparatively soft spectrum.

3. A flare occurs beyond the limb and generates particles according to alternative 2; however, because of heliolongitudinal remoteness, they do not show up at the earth. Moreover, when the loop structure of Fig. 2 is present, the propagating magnetic bottle stimulates reconnection of the lines of force and the formation of a current layer with subsequent rapid acceleration of an appreciable number of particles to high energies. If this process occurs near the favorable connection longitude ($\theta_\delta \approx 82^\circ$W), then the accelerated particles reach the earth unhindered. The burst of hard X-ray radiation was evidently related to the injection of part of the accelerated particles into the lower layers of the solar atmosphere. However, judging from the very hard spectrum (Fig. 3b), it would be

difficult to expect noticeable emission of soft X-ray radiation and the H_α line. Thus, of the possibiltiies for explanation of the event of February 16, 1984, discussed above, alternative 3 is the most suitable in our opinion.

The generation and emission of particles of the rapid component occurs even prior to the opening of the magnetic bottle, whose mean lifetime amounts to $\sim 10^3$ s [5]. The acceleration in the models with magnetic reconnection occurs in a time $T_a \sim 1 \div 10$ s [14]; the shape of the spectrum differs in a decrease of the slope in the low-energy region, which one can see in Figs. 3 and 4 in the calculated spectra of generation of the rapid component. The strong shock wave gives a strictly power-law spectrum in the rigidities, which contradicts the result of [25] already noted and spectrum *1* in Fig. 3b calculated by us. For example, a model of stochastic acceleration [31] by MHD inhomogeneities of the solar plasma gives a smoothly varying shape of the spectrum (in the form of Bessel curves). However, estimates [14] show that the effectiveness (rate) of the stochastic mechanism is insufficient to explain the pulsed acceleration of SCRs. In addition, upon the specification of an identical acceleration rate for protons and electrons, the calculated spectrum of the electrons turns out to be steeper than the observed one.

As is evident from Figs. 3 and 4, the spectrum of the rapid component lies below the spectrum of the global flux and merges with it at energies ε = 3-4 GeV, which may indicate that the entire flux at high energies is caused just by the rapid component. The spectra of the rapid component, calculated with the model of [9] and (10] for the actual parameters of the magnetic field and density of the plasma, are in good agreement with the spectra at the source obtained from observations in the 0.3-5 GeV energy range, which argues in favor of this mechanism of generation of the rapid component. The parameters selected for calculation of the generation spectra, which match the spectra obtained from the observational data, correspond to coronal altitudes $h \sim 0.5\text{-}1R_\odot$. One should note the almost complete identity of the spectrum of the rapid component in the December 7, 1984, event (Fig. 4) and the emission spectrum in the February 16, 1984, event (both of these events were similar in intensity). In the event of February 23, 1956, which appreciably exceeded in its power those indicated above, the calculated values n, B, and L turned out to be larger, but they also correspond to generation altitudes $\geq 0.5R_\odot$ in the corona.

Moreover, in the low-energy region, the calculated values of the generation spectrum of the rapid component lie lower in Figs. 3 and 4 than the spectra obtained from observations. This difference may be related to the neglected contribution of soft particles generated in the pulsed phase of the flare and escaping from the closed magnetic configuration (Fig. 2d).

In the region of very high energies, ≥5 GeV, there is also a tendency for the flux of the rapid component to exceed that calculated with formulas (3)-(5). A possible cause of this may be the fact that the configuration of Fig. 2d permits particles trapped in the bottle to cross repeatedly the acceleration region (the current layer) prior to their ejection into interplanetary space. In this case, the intensity will be higher in the high-energy region of the spectrum of accelerated particles than that predicted by the relationships (3)-(5), which assume single scattering.

When SCRs move into the IMF, the so-called coherent mode of propagation [32, 33] is theoretically possible. The appearance of a narrow intensity peak accompanied by a slowly varying "ship's wake trail" [34] (the temporal profile of the intensity I in Fig. 1 is a typical example) can serve as its trademark characteristic. The coherent peak (crosshatched part) and the diffusion cavity (ship's wake trail) are formed in the theory of focused diffusion [32, 33] in the process of evolution of a pitch-angle distribution which is isotropic in the source. However, as has been shown [34], for values of the transport free path $\Lambda \gtrsim 1$ AU (which corresponds to the estimates of Λ for the events of December 7, 1982, and February 16, 1984, a Type *1* profile (Fig. 1) with a large value of the intensity of the coherent peak can be observed only in the case of an anisotropic source on the sun. A current layer (Fig. 2) can serve as such a source if it is formed high enough in the corona, near open coronal structures [2, 3]. The anisotropic nature of SCR emission in the event of February 16, 1984, with a rapid component has been shown in [24]. On the basis of an analysis of data on γ emission of the flare of June 3, 1982, the authors of [35] also assume the existence of two sources of accelerated particles, one of which is located at a low altitude (in a close magnetic configuration), and the other is located high in the corona (in a region with open lines of force). However, one can also explain those very same data (as well as similar data for the event of December 7, 1982) within the framework of a single acceleration model with the subsequent capture of particles in a magnetic loop [17].

The effects of the drift of the SCRs into the IMF, which lead to longitudinal drift of the particles, have been discussed [36]. Longitudinal drift in the coronal magnetic field [2, 3] is possible for the rapid component; however, upon propagation into the IMF, the effects of drift may not be appreciable because of the strong collimation of the particles [32]. In addition, the softening of the energy spectrum predicted in [36] has not been observed for the rapid component, which is always characterized by a very hard spectrum.

CONCLUSIONS

1. The generation of particles of the rapid component occurs at coronal altitudes $(0.5\text{-}1R_\odot)$. Acceleration in a current layer which arises on the periphery of a magnetic bottle upon its reconnection with a neighboring magnetic loop or with a bottle having the opposite direction of the magnetic field is the likely generation mechanism.
2. The indicated mechanism explains the peculiarities of the spectrum of particles of the rapid component in the 0.3-5 GeV energy range.

The use of combination models of the acceleration is necessary to explain the complete spectrum of SCRs.

3. The remoteness of the generation (and emission) site of the rapid component from the flare region may be related to the fact that the current layer in which the particles of the rapid component are accelerated develops on the periphery of a magnetic bottle separated from the flare site by a distance of 50° in heliolongitude.

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