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LARGE GROUND LEVEL EVENTS IN SOLAR CYCLE 22 AND SOME PECULIARITIES OF RELATIVISTIC PROTON ACCELERATION

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ABSTRACT

Some of the Ground Level Enhancements of Solar Cosmic Rays (SCR) recorded by neutron monitors during solar cycle 22 are analyzed. The events appeared in series, and their occurence rate in 1989-1991 was a factor of 4 larger than the average value (≃ 1/yr) for the total observation interval (since 1942). The events of Sept. 29 and Oct. 24, 1989 proved to be the more intensive. The analyzed events show no peculiarities as to the distribution of the $T_{1/2}$ parameter, whereas the shape of the profile of some events is notable for a two peak structure. The later implies the possibility of a two component SCR ejection from two different sources in the solar atmosphere. For the event of Sep. 29 we have estimated the ejection rigidity spectrum of protons to be $D_\odot(R) = (1\text{-}2)\ 10^{32} R^{-2.9}\ \mathrm{Gv}^{-1}$ at $R \geq 1$ Gv. As to its proton flux, this event proved to be by 1-2 orders less intensive than the well known event of Feb. 23 1956.

INTRODUCTION

Solar proton events (SPE) in the current solar cycle 22 display some peculiarities of special interest /1/. For physical and practical reasons the most intensive SPE are often classified in a specific group. Then the data on these events can be used either to estimate the highest potentialities of the solar accelerator (e.g. the events of Feb. 23, 1956 and Sept. 29, 1989 with abundant fluxes of very energetic particles), or to simulate a "worst case" from the point of view of radiation hazard (e.g. the events of July 1959, Aug. 1972, and Oct. 1989 with huge fluxes of moderate energy protons). Below we analyze Ground Level Enhancements (GLE) data obtained during 1989-1991 and estimate some generation and propagation parameters for relativistic protons.

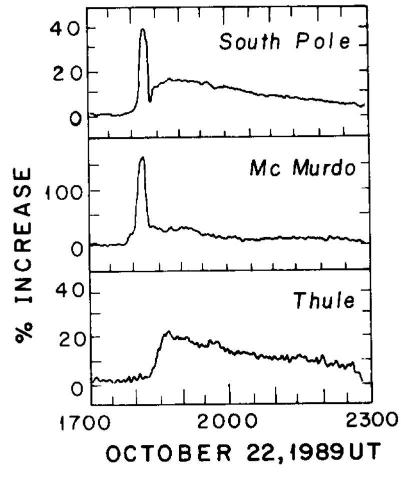
OBSERVATIONAL DATA

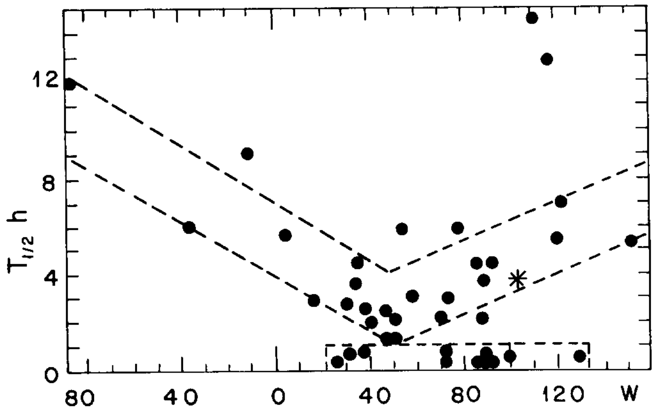
Out of the 52 GLEs observed from 1942 until the present 13 events have been recorded in the current solar cycle. Table 1 contains their basic characteristics obtained from 1 or 5 min. data from the Apatity neutron monitor (geomagnetic cut-off rigidity $R_c = 0.6$ GV). It is evident that the Sep. 29 and Oct. 24, 1989 events were the most intense of the 13 GLEs. The GLEs occurred in series (it is especially well seen in May 1990 when 4 events were produced by one and the same active region in the Sun). The occurrence rate of events during 1989-1991 was by a factor of 4 larger than their average occurrence rate ($\sim 1\ \mathrm{yr}^{-1}$) for the whole period of SCR observation. The event of the greatest interest is obviously that of Sep. 29, 1989, which takes up the third place in the hierarchy of GLEs after the SPEs of Feb. 23, 1956 and Nov. 12, 1949 /2/. We characterize the GLEs by their $T_{1/2}$ parameter (full width of the intensity-time profile at its half height). Fig. 1 shows this parameter as a function of heliolongitude of the respective flare site (SCR source) for 41 GLEs. From Table 1 and Fig. 1, one can see that the events in cycle 22 have no peculiarities in the $T_{1/2}$ distribution compared to the other events: the magnitude of $T_{1/2}$ for 13 events changes from 0.2 h (Nov. 11, 1989) to 3.8 h (Oct. 19, 1989). Only 3 events proved to of the prompt kind ($T_{1/2} < 1$ h). However the shape of the time profile of a number of events displays some features that possibly imply the presence of two SCR components - a prompt and slow (delayed) ones /3/. For example, Fig. 2 illustrates the time profiles of the counting rate obtained by neutron monitors at Apatity and Oulu during May 21-22, 1990. This event is classified as a prompt one ($T_{1/2} = 0.7$ h), and the time profile in Fig. 2 displays a distinct two-peak structure. The first (sharp) peak corresponds in our opinion to the arrival of the prompt component, and the second (smoother) peak is probably due to the delayed component. Similar effect was observed on Oct. 22, 1989 at the Antartic stations South Pole and McMurdo (Fig. 3) /4/. It is interesting to note that in the Northern hemisphere (at Thule, Greenland) the time profile of this event displayed no such peculiarity (i.e. it was smooth enough), and according to the Apatity NM data, the event was not classified as a prompt one ($T_{1/2}$= 2.9 h). A less distinct but noticeable two-peak structure was observed at Apatity during the event of May 1990 ($T_{1/2}$= 0.3 h).

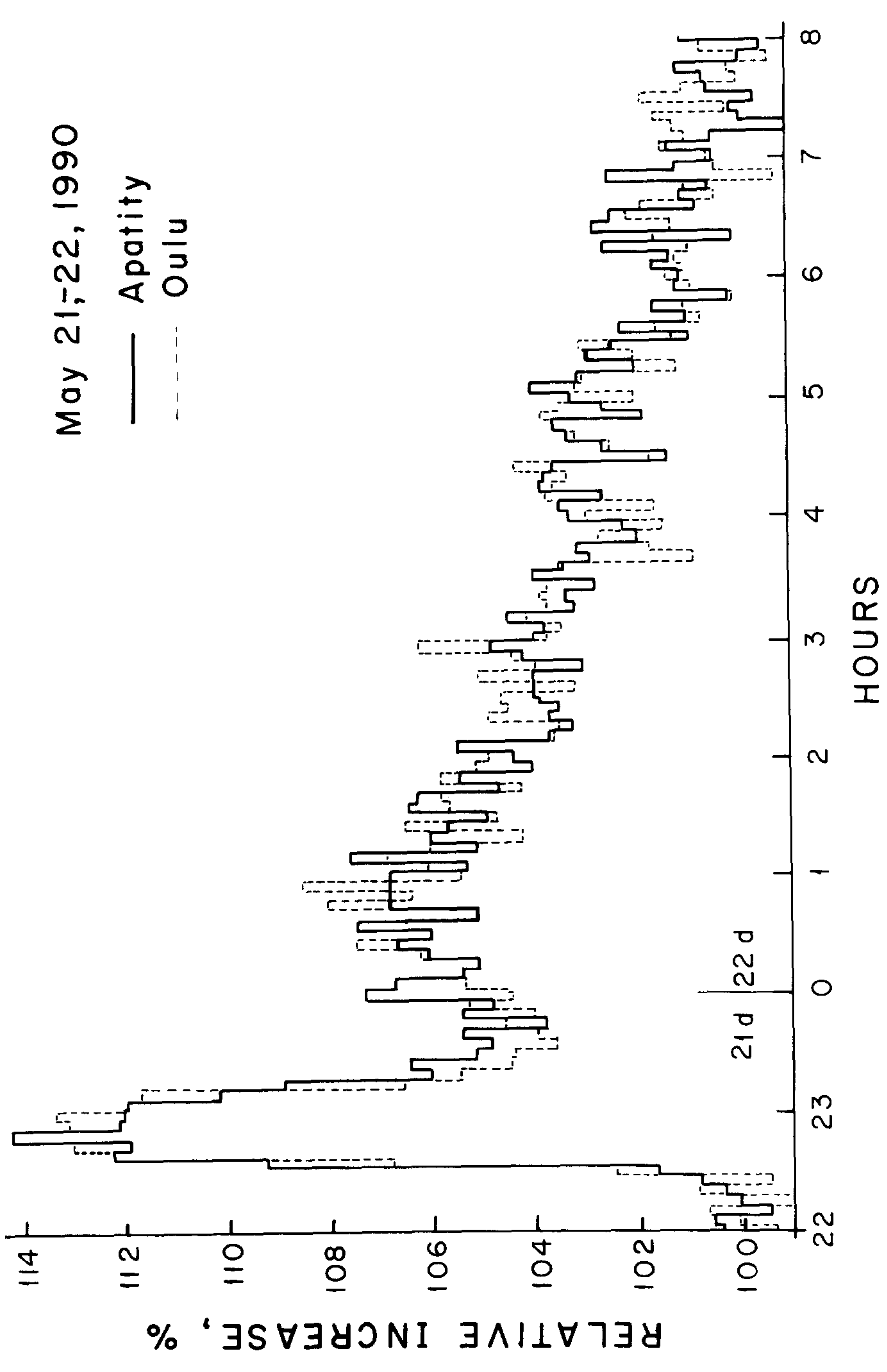
Certain evidence of a similar effect was obtained for the SPE of Sep. 29, 1989 e.g., from the NM data from Apatity, Deep River, Calgary, etc. /5,6/. It is interesting to note that the apparent direction towards the source of particles changed in time: at the event onset (the first peak at 1217 UT) the source was north of the ecliptic, and about 1 h later (the second peak at 1315 UT) it moved to the southern hemisphere of the Sun. The event was notable for its very hard complex spectrum. The authors /7/ believe that the peculiarities of the time profile mentioned above are indicative of the two-fold ejection of SCR on Sep. 29, 1989.

Characteristics of SCR Source of Sep. 29, 1989

Relativistic protons recorded on Sep. 29, 1989 were obviously generated by a large post-limb flare which manifeste itself in the X-rays range (X9.8 at 1047 UT). As shown by radio observations at 5.2 cm /8/, the flare was preceded by eruption of an extended filament south of AR 5698 with subsequent coronal mass ejection. The latter resulted in occulation of the S-component source over the AR between 0705 and 0757 UT. The degree of radio wave polarization, the high brightness temperature and the large altitude served as additional signatures of pre-flare situation in the case under consideration. The magnetic field configuration above AR 5698 remained unknown, however a spectacular loop structure was distinctly observed for more than 10 h /9/. The whole complex of these data allows us to apply to the Sep. 29 event our hypothesis /10/ of two different acceleration sources that produce the prompt and the delayed SCR components (peaks I and II, respectively). The source of the prompt component may be situated high in the corona, far from the site of the flare that generates the delayed component.






May 21-22, 1990
Apatity
Oulu
RELATIVE INCREASE, %
114
112
110
108
106
104
102
100
22
23
0
1
2
3
4
5
6
7
8
21 d
22 d
HOURS

Propagation Parameters of SCR on Sep. 29, 1989

If the event under consideration is produced by two particles sources separated in time and space, the analysis of SCR transport becomes not a trivial task because the source sites and times are not known exactly. Proceeding from /6/, it can only be stated that the time shift between two ejections does not exceed 1 h. Further, the two SCR components can be assumed to superimpose near the Earth orbit, so that without discriminating between them, the analysis of the time profiles in order to determine the diffusion parameters is of no special interest. However it seems important to estimate the applicability of diffusion models for a quantitative description of data, at least at a late stage of the event ($t \geq t_{max}$).

Our analysis is based on the data from three neutron monitors: Moscow (R_c=2.35 GV), Apatity (R_c= 0.6 GV), and Mirny (R_c= 0.02 GV). The first step was to study the data in order to select an adequate SCR propagation model. For this purpose, the time profiles at the decay stage were fitted for different times by exponential and/or power law functions (with characteristic decay time τ_α, and/or exponent, α, respectively). Then, the statistical average values, $\bar{\tau}_\alpha$ and $\bar{\alpha}$, were calculated. These parameters proved to be similar for NM Apatity and Mirny: $\bar{\tau}(AP) = 4.4\pm0.5$ h, $\bar{\alpha}(AP) = 2.25\pm0.3$, $\bar{\tau}_\alpha(Mr) = 4.4\pm0.5$ h, $\bar{\alpha}(Mr) =2.15\pm0.7$. According to our estimates, the decay stage at these stations is fitted by the power law function better than by the exponential one, which imposes some restrictions when selecting a suitable diffusion model. The selection is more difficult when the NM Moscow data are used ($\bar{\tau}_\alpha = 2.75\pm0.3$ h, $\bar{\alpha} = 1.05\pm0.35$). The propagation process is obviously more complicated at particle rigidites R > 2.35 GV than at R ≤1 GV.

We have used as a propagation model the solution of the differential equation /11/ at $\text{æ}_\parallel(r) = a\text{æ}_\perp(r)$, where $\text{æ}_\parallel$ and $\text{æ}_\perp$ are the diffusion coefficients along and across the radial direction, and $\text{æ}_\parallel \sim r^\beta$, where $\beta \geq 0$. The source is assumed to be point-like and instantaneous. The time profiles for the three stations mentioned above are properly fitted by the solution /11/ at $t_{max}(Ap) = 7500$ s, $t_{max}(Mr) = 7200$ s, $t_{max}(Ms) = 3900$ s; $\beta = 0.7$ (only for Apatity and Mirny). By assuming the solution /11/ to be a Green function of integral equation and proceeding from observations at $t \leq t_{max}$, we can solve an inverse problem, namely, to reconstruct the ejection time profile and energy spectrum of SCR near the Sun. In accordance with estimates /12/, it can be assumed that $\text{æ}_\parallel \sim \varepsilon^{0.5-0.8}$, where ε_k is the kinetic energy of protons.

One can also use as a Green function the solution of the diffusion equation /13/ for the limiting case of a very strong magnetic field, provided the dependence $\text{æ}_\parallel(r) \sim r^\beta$ is taken into account. We do not consider the problem in a more general form when $\text{æ}_\parallel \sim r^\beta$ and $\text{æ}_\perp \sim r^\sigma$, because the solution proves awkward and the relation between β and σ is indefinite. As shown in /13/, anisotropic (one-dimensional) diffusion is to be observed at the beginning of the event, which later on becomes isotropic (three-dimensional). Our preliminary (and not accurate enough) calculations using the modified solution /13/ yield the differential spectrum of relativistic protons near the Sun in the form $\sim R^{-\gamma_\odot}$, where $\gamma_\odot = 4\pm1.5$. The characteristic time of SCR ejection at $\varepsilon_k > 1$ GeV is estimated to be $\tau_\odot = 20\pm10$ min. The estimation accuracy can apparently be improved by choosing a more adequate propagation model.

By assuming $t_{max}(Ap) = 2$ h, $\varepsilon_k^{ef} \geq 2$ GeV and by supposing the time profile at Apatity to be formed due to transverse diffusion, we obtain $\text{æ}_\perp = r^2/6t_{max} = 5.2\ 10^{21} cm^2 s^{-1}$. On the other hand, taking a typical value of $\Lambda_\parallel(2\ \text{GeV}) = 3.3\ 10^{12}$ cm /12/, we obtain $\text{æ}_\parallel = \Lambda_\parallel v/3 = 3.1\ 10^{22} cm^2 s^{-1}$. Hence, a somewhat delayed stage of intensity increase in the energy range of 2 to 10 GeV observed on Sep. 29, 1989 can be explained by transverse diffusion at $\text{æ}_\perp/\text{æ}_\parallel \leq 0.165$. These estimates make sense, provided there was only one SCR source. If there were two sources, the diffusion consideration seems valid only for the first peak of the time-intensity profile of the Sep. 29, 1989 event, whereas the second peak was not likely due to the relativistic proton beam that propagated along the IMF force lines up to the Earth orbit practically without scattering. The latter assumption is corroborated by the time behaviour of proton anisotropy at R ≥ 3 GV /6/.

SCR Source Spectrum

Some uncertainty as to the sites of the Sep. 29, 1989 SPE sources makes impossible the use of diffusion models to reconstruct the spectrum of generated (ejected) particles with sufficient reliability (e.g., see /14,15/).

Thus, we have made an attempt to estimate the SCR ejection spectrum from the first peak data (1217 UT) by using an approximate technique /10/. The differential spectrum of the directional SCR flux, observed at this time was /6/: $D^{I}_{\oplus}(R) = 9.32\ R^{-2,9} cm^{-1} sr^{-1} GV^{-1}$. Neglecting the scattering of relativistic protons on their way from the Sun to the Earth, we obtain the upper estimate for the ejection spectrum $D^{I}_{\odot}(R) = (1 - 2)\ 10^{32} R^{-2.9} GV^{-1}$. Hence, the largest possible number of ejected protons at R ≥ 1 GV did not exceed $N^{I}_{\odot}(\geq 1\ GV) \sim 10^{32}$. For the second peak (1327 UT), the SCR spectrum near the Earth was $D^{II}_{\oplus}(R) = 15.2\ R^{-3} cm^{-2} s^{-1} sr^{-1} GV^{-1}$/6/ and the ejection spectrum was $D^{II}_{\odot}(R) = (1.6-3.2)\ 10^{32}\ R^{-3}\ GV^{-1}$, resulting in practically the same estimare of $N^{II}_{\odot}(\geq 1\ GV) \leq 10^{32}$ as for peak I.

It is interesting to compare the data on the spectra and absolute intensities of relativistic proton for two events of Feb. 23, 1956 and Sep. 29, 1989. According to our estimates /10/, the directional flux spectrum of SCR on Feb. 23 near the Earth can be fitted by $D^{d}_{\oplus}(R) = 5\ 10^{2} R^{-3.5} cm^{-2} s^{-1}\ GV^{-1}$. When comparing these results to /6/, one can see that the Sep. 29 event was by 1-2 orders of magnitude less intense in its proton flux at R ≥ 1 GV than the event of Feb. 23. Similar conclusion follows from comparison of the ejection spectra $D^{I}_{\odot}$ and $D^{II}_{\odot}$, obtained above for the Sep. 29 event to the spectrum of the Feb. 23 event /10/ $D_{\odot}(R) = (1.1 - 2.2)\ 10R^{-3.5\pm0.2}\ GV^{-1}$, whence it follows that $N_{\odot}(\geq 1\ GV) \leq 10^{33}$.

CONCLUDING REMARKS

The analysis of relativistic SPEs in solar cycle 22 has revealed a number of discrepancies and uncertainties in interpretation of the spectral, temporal and angular characteristics of SCR. The interpretation difficulties arise partly from the increased precision of ground-based observations that have revealed a detailed fine structure of SPEs. These cannot be described by any particular model of particle production and transport in terms of the generally accepted concepts. For example, it is still unknown why GLEs are observed in series with the events following one another during several days, though their average rate is ~ 1 yr^{-1}. This effect is most likely due to a certain specific magnetic field configuration in the corona which exists for a long time and evolves as the active region develops. So, a comprehensive description of the main parameters of the Sep. 29, 1989 event requires the development of an up-to-date model of two-component ejection of accelerated particles /10/. The first impulsive (spike-shaped) increase at 1215-1230 UT that was even recorded by underground muon telescopes with the effective energy up to 120 GeV /15/ was probably caused by particles accelerated high in the corona as a result of magnetic field reconnection. The highest possible SCR energy ensured by this mechanism is 250 GeV /10/.

Though the flare of Sep. 29 occurred behind the W limb, the base of the IMF force line connecting the Earth and the Sun was projected onto the visible disk in the region of an open structure streched along the equator - the interplanetary current sheet /18/. The flare under consideration was followed by loop-like coronal magnetic fields observed high above the photosphere /19/. Such a configuration of magnetic fields near the Sun might have favoured prompt arrival of particles from a high coronal source.Moreover, we do not rule out the possibility that interaction between coronal loops and the neutral current sheet has stimulated magnetic reconnection and particle acceleration /10/. Accelerated particles left the Sun inmediately escaping to interplanetary space along the open field lines. This process was followed by particle focusing in the divergent magnetic field, which probably resulted in the very strong anisotropy observed during 5 h after the event onset.

The second ejection was smoother that the first one, and it was most likely related to the particles released from the magnetic bottle. By drift and diffusion in the solar corona /20/, these particles were transported to the base of the interplanetary current sheet where the Earth was at the moment of the Sep. 29, 1989 flare /18/. The prompt needle-shaped increase of SCR on Oct. 22, 1989 was observed only at two Antartic stations - South Pole and McMurdo. It may be explained by strong north-south anisotropy of SCR along the apparent IMF direction. Similar anisotropy is quite frequently observed in the events with relativistic protons. We suppose that the event under consideration is due to large-scale structures in the solar wind. One of these termed the "planar magnetic structure" (PMS) has recently been identified /21/. It persisted for several hours and made a significant angle with the plane of the ecliptic. Numerical calculation of the particle motion in these structures is a difficult task.

Table 1 Ground Level Events of 1981-1991 from the NM Apatity Data

Date	Type II onset UT	Helio-coordinates	Importance		NM Apatity				
			X-rays	Hα	Onset	Max	T_p, min	$T_{1/2}$, h	Increase, %
12.10.81	0625	S22 E35	X3.1	3B	0635±5	0910±5	22±5	6	10.3
26.11.82	0226	S12 W84	X4.5	SN	0300±5	0455±5	43±5	5	4.6
7.12.82	2345	S19 W86	X2.8	1B	2400±5	0020±5	23±5	0.5	28
16.02.84	0858	– W132	–	–	0910±5	0915±5	20±5	0.5	13
25.07.89	0844	N25 W84	X2.6	2N	0850±5	1025±5	34±5	2.3	3.8
16.08.89	0118	S16 W84	X20	2N	0136±1	0340±5	26±1	3.4	12.5
29.09.89	1133	S24* W105*	X9.8	–	1150±1	1350±5	15±1	3.9	202
19.10.89	1258	S27 E10	X13B	4B	1319±1	1545±5	29±1	9.8	38
22.10.89	1805	S27 W31	X2.9	2B	1808±1	1830±5	11±1	2.9	17
24.10.89	1831	S30 W57	X5.7	3B	1830±1	2035±5	7±1	6.5	95
15.11.89	0650	N11 W26	X3.2	3B	0708±1	0712±1	26±1	0.2	8
21.05.90	2219	N35 W36	X5.5	2B	2232±1	2255±5	21±1	0.7	14
24.05.90	2051	N33 W78	X9.3	1B	2145±5	0035±5	62±5	5.7	8
26.05.90	2058	– W100*	X1.4	–	2124±1	2148±1	34±1	0.3	7.5
28.05.90	0433	– W120*	C1	–	0535±5	1015±5	70±5	7.5	5
11.06.91	0209	N31 W17	X12	3B	0240±5	0330±5	39±5	2.6	8.5
15.06.91	0821	N33 W69	X12	3B	0846±1	0925±5	33±5	1.6	26

*Indirect estimate; T_p – propagation time of the first arriving particles; $T_{1/2}$ – full width of the intensity-time profile at the half peak height.

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