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CHARACTERISTICS OF THE 29.09.1989 GLE OBTAINED FROM OBSERVATIONS AND MODELLING

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Abstract. The GLE of September 29, 1989, the most powerful for the last 40 years, had the two-maxima structure and was marked also by very complicated anisotropy behaviour. The characteristics of the relativistic solar cosmic rays (SCR) in the event have been studied by modelling the increase effect at 42 neutron monitor stations of the world-wide network and fitting them to the experimental data. The refined solar proton parameters: rigidity spectrum, pitch-angle anisotropy and anisotropy axis directions were obtained in frame of checking up the two working hypothesis: the unidirectional and bidirectional anisotropy during the second increase. The last one showed decisively better agreement with the observations which may be an indication of the loop-like structure of the interplanetary magnetic field (IMF) during the event of 29.09.1989.

Introduction

The September 29, 1989 GLE was not only the greatest one in intensity for the last 40 years but it was remarkable also by very complicated intensity-time profiles at different neutron monitor stations as well as unusual behaviour of the anisotropy and energy spectrum of the relativistic solar protons (*Smart et al.*,1991, *Cramp et al.*, 1993, and many others). In our previous studies (*Vashenyuk et al.*, 1993, 1995, 1997) the complexity of the intensity profiles during the event were interpreted as possible twofold ejection of relativistic solar protons from the Sun and bidirectional anisotropy in high-energy solar proton flux during the second intensity maximum. The recent study based on a modelling technique allowed us to obtain the refined parameters of relativistic solar protons during the 29.09.1989 GLE, i.e.: rigidity spectrum, pitch-angle distribution and anisotropy. The most important result of this study is confirmation of the previous conclusion of the authors about the bidirectional anisotropy during the second increase.. The latter may be an indication of the loop-like structure of the IMF during the event.

Modeling technique

One of the key problems in the GLE modelling is computation of asymptotic approach directions of the incoming to the magnetosphere particles. For this purpose trajectory calculations of a negatively charged particle starting at a station location point on the surface of earth have been performed. The relativistic equation of motion of a charged particle in the geomagnetic field is:

$$\gamma m(\partial^2 \mathbf{r} / \partial t^2) = Ze(\partial \mathbf{r} / \partial t)\times\mathbf{B} \qquad (1)$$

where γ is the Lorentz-factor, r is the radius-vector, **B** is the magnetic induction vector, Ze and m are the charge and a mass of a particle, respectively. The numerical integration was performed by the Runge-Kutta- Felberg method of the 4th-5th order. The magnetospheric field was represented by the Tsyganenko 89 model with $K_p = 2$, so was the magnetic activity during the event. Characteristics of primary solar protons outside the magnetosphere have been obtained by solving an optimisation problem to find optimal parameters of the function describing the relative increase effects due to the solar cosmic rays (SCR) at different neutron monitor (NM) stations. The response of the j-th NM station to the anisotropic solar proton flux is given by the relation (sf. [*Shea and Smart*, 1982]):

$$\Delta N/N)_j = K \int_{R_{cj}} J_{\parallel}(R)F(\theta_j(R))S(R)\, dR, \qquad (2)$$

where j is the station index, $(\Delta N/N)_j$ is the relative increase effect (in respect to the galactic background) at the j-th station , K is the coefficient of proportionality; $J_{\parallel}(R)$ is the parallel to the anisotropy axis differential solar proton flux

$$J_{\parallel}(R) = AR^{-\gamma} \text{ (particles/ (cm}^2\text{ s ster GV))}, \qquad (3)$$

where γ is monotonously decreasing by $\Delta\gamma$ per 1 GV for $R \geq 2$ GV [*Cramp et al.*, 1993], S(R) is the specific yield function [*Debrunner et al.*, 1984]. The pitch-angle distribution was suggested to have the form:

$$F(\theta) = \exp(-\theta^2/C) \qquad (4)$$

where θ is the angle counted off the anisotropy axis (the last one is usually parallel to the IMF vector). With the Legendre principle being applied (*Shchigolev*, 1969) the system of constrained equations may be reduced to the nonlinear least square problem:

$$SN=\sum((\Delta N/ N)_{jCALC} - (\Delta N/ N)_{j\,EXP})^2 \rightarrow \min \qquad (5)$$

A quality of the optimization results was estimated by a rest error defined by the formula:

$$\varepsilon = SN/ \sum (\Delta N/N)^2_{j\,EXP} \qquad (6)$$

where indexes CALC and EXP mean calculated and experimentally measured values, respectively.

Observations

An extremely complex behaviour of the time and spatial distributions of the relativistic SCR flux during the 29.09.1989 GLE is shown in Fig.1 where the intensity profiles of four NM stations are illustrated. The main feature of the event was a twofold ejection of the relativistic protons from the Sun causing the double maximum increase at some NM stations (*Vashenyuk et al.*, 1993, 1995, 1997) and Fig.1 also demonstrates very complicated anisotropy behaviour. A remarkable detail here is the difference of the intensities registered by the closely located NM stations Apatity and Oulu during the second increase. As the stations were looking in the antisolar direction, *Vashenyuk et al.*, (1997) suggested existence of the anisotropic SCR flux from this direction which they attributed to a possible bidirectional anisotropy. Such anisotropy is often observed in low energy solar particles and related to the loop-like structure of the IMF (*Palmer et al.*, 1978, *Richardson et al.*, 1991).

Modeling

In modelling the 29.09.1989 GLE parameters the data of 42 NM stations of the world-wide network have been used. The two working hypotheses have been tested: 1) unidirectional anisotropic particle flux in the interplanetary medium described by the relation:

$$J_j(R)=J_{\|}(R)F(\theta_j(R)) \qquad (7)$$

and 2) bidirectional particle flow along the calculated anisotropy axis:

$$J_j(R)=J_{\|1}(R)F_1(\theta_{j1}(R))+J_{\|2}(R)F_2(\theta_{j2}(R)) \qquad (8)$$

where the energetic spectrum and pitch-angle distribution are given in accordance with (2) and (3), but they are different and independent of each other both for unidirectional (7) and bidirectional (8) source fluxes. The results of the modelling are displayed in Table 1.

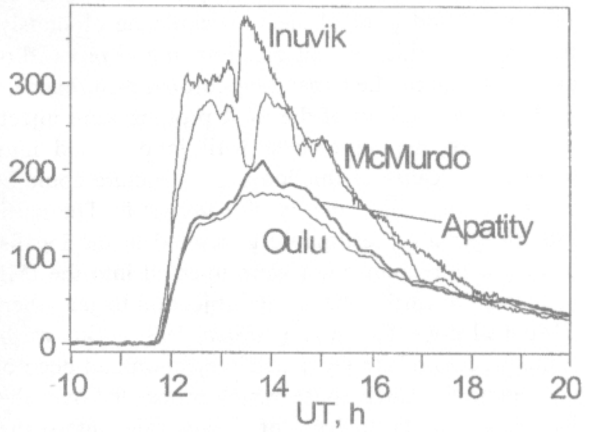

Fig.1.The second increase in the 29.09.1989 GLE. Note the intensity difference between the closely located Apatity and Oulu stations indicating a possible sunward anisotropy.

Table 1. Optimised SCR parameters obtained for the unidirectional and bidirectional sources.

Source		UT	A	γ	Δγ	C	Latitude, degrees	Longitude, degrees	ε
Unidirectional		12.25	1.94	1.08	0.13	3.41	17.2	258.9	2.62
		13.25	66.93	3.53	0.13	9.39	-9.3	266.9	1.47
		16.05	148.2	4.96	0.15	9.05	-50.1	305.8	2.23
Bidirectional	Source 1	13.25	101.5	3.59	0.20	4.07	-4.4	285.7	0.54
	Source 2	13.25	23.25	3.80	0.0	1.20	4.4	105.7	

The data obtained by the optimisation procedure are in general agreement with the results of the qualitative consideration presented above. The first increase was very hard: $\gamma\approx1$ with rather narrow pitch-angle distribution $C\approx3.5$. The second increase was softer ($\gamma\approx3.5$) and the spectrum continued getting softer having reached the value of $\gamma\approx5$ at 16 UT (Table 1). This spectrum recalculated for the energy scale is shown in Fig2. By triangles in the figure is shown the solar proton spectrum obtained by direct measurements made with balloon flown over Apatity at the same time. One can see a good agreement between the calculated and measured intensities in the energy range of several hundred MeV. A small difference increasing with energy may be caused by the anisotropy effect. The calculated spectrum corresponds to the maximum direct flux coming from the Sun along the anisotropy axis. But the asymptotic cone for Apatity over which the balloon flew, was looking in the opposite direction at that time of day. So the difference may also be caused by disagreement of the observations with the unidirectional model predictions for 16.05 UT (Table 1). The anisotropy at the beginning of the event was directed to the west of the "garden hose" direction and slightly (17°) to the North from the ecliptic. And then it progressively rotated to the South having reached the value of $\theta\approx-50°$ at 16 UT (Table 1).

Fig.3 shows asymptotic cones calculated for a number of NM stations at the moment of the second intensity maximum (13.25 UT). The coordinates are GSE and their centre corresponds to the direction to the Sun. The blacked circle marks the anisotropy axis direction for the direct (from the sun) flux, which is rather close to the one for the unidirectional case (Table 1). And the empty circle shows the calculated axis of the reverse flux which, is between asymptotic cones of Apatity, Oulu, Goose Bay and Mirny indicating close intensities during the second increase (Figs.1 and 2). So one can see that the bidirectional model is better than unidirectional one in describing the data of observations. The bidirectionality in the low-energy particle domain is often suggested for identification of the loop-like structure of the IMF (*Palmer et al.*, 1978, *Richardson et al.*, 1991). The situation when energetic solar particles were injected into the roots of a large-scale interplanetary loop was described in [*Richardson et al.*, 1991]. Moreover, the relativistic SCR also showed the bidirectionality in this case [*Cramp et al.*, 1995]. We believe that the similar situation could take place during the 29 .09.1989 GLE. The first rigid and prompt ejection near 12 UT proceeded during the impulsive phase of the flare (*Vashenyuk et al.*, 1997). It was highly anisotropic and unidirectional (Table 1). The second gradual ejection could be obviously related to the CME. As this kind of ejection should proceed over a wide area occupied by the expanding coronal disturbance, one cannot exclude a possibility of the SCR protons were injected into the two legs of the large-scale IMF loop rooted into the solar corona. The cause of this loop-like structure could be the CME eruptions, preceding the 29.09.1989 GLE. The particles of the prompt ejection presumably generated in the localised process of magnetic reconnection were injected into the IMF field line connected to earth. The second injection began when the top of CME had gone far away (*Kahler*, 1994). But we believe that some process of the DC particle ejection had been operating in the behind the CME space which proceeded over the wide area including the both legs of large-scale interplanetary loop. Particles of this delayed population could be injected into the both legs of the loop and formed the bidirectional anisotropy.

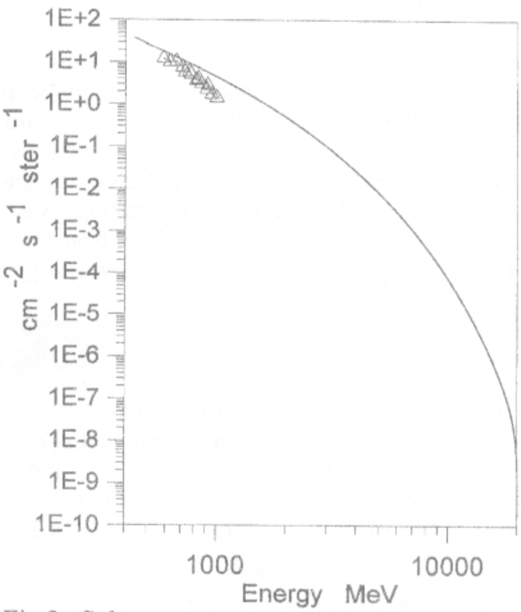

Fig.2. Solar proton energetic spectra for th time period around 16 UT: solid line is th modeled spectrum obtained from the rigidit one at 16.05 UT(Table 1), triangles mark th spectrum measured at the same time by balloo over Apatity.

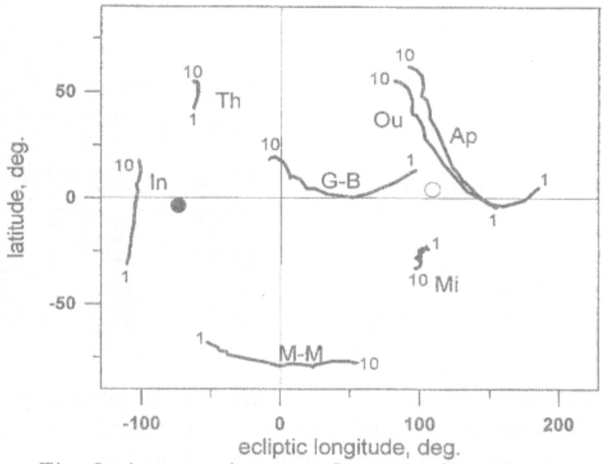

Fig. 3. Asymptotic cones for a number of neutron monitors (Thule, Inuvik, McMurdo, Goose Bay, Mirny, Oulu and Apatity) at 13.25 UT 29.09.1989.The blacked and open circles mark the axes of the direct and reverse SCR fluxes in the bidirectional model, Table 1

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