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Generation and propagation characteristics of relativistic solar protons during the GLE of September 29, 1989.

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ABSTRACT

The GLE of September 29, 1989 was not only the largest over the last 40 years. It was marked also by a number of unusual features such as the strong variation with time of the energetic spectrum and the anisotropy direction. We try to explain these features in the frame of conception of two component-relativistic solar cosmic rays: the prompt and delayed one.The first, prompt component (PC) was suggested to originate from impulsive phase of the behind-limb flare. It had a hard energy spectrum, a short duration and the anisotropy directed out of the Sun. A source of the particles seemed to be well aside of the flare and was connected with the magnetic merging in the solar corona as could be seen from the specific form of the energetic spectrum. The second, delayed component (DC) was ejected from the Sun ~1 hr later. It had a soft energetic spectrum characteristic for the stochastic acceleration mechanism and, perhaps, a bidirectional anisotropy as could be deduced from the neutron monitor observations. This bidirectionality may be explained if to suppose that the IMF during the event had a shape of giant loop with its both ends rooted into the Sun. The source of the DC presumably occupied the wide area, as large as CME. So the particles of DC could be injected into the both ends of the loop forming the bidirectional anisotropy. This looped IMF structure was possible created by solar eruptions, preceding the September 29, 1989 GLE.

INTRODUCTION

The September 29, 1989 GLE was not only the greatest in its intensity but it was remarkable also by the very complicated intensity-time profiles at different neutron monitor stations (Smart et al., 1991 and many others).The low-latitude stations (Alma-Ata, Tokyo, etc.) registered a single, highly anisotropic intensity maximum at the very beginning of the event. This increase was also registered by the underground detectors in Embudo, NM, USA (Swinson and Shea, 1991) and Yakutsk, Russia (Krymski et al., 1990). On the other hand, a number of high-latitude stations (for instance, Deep River and Goose Bay) demonstrated the double maximum which can be interpreted as indication of two SCR components (Vashenyuk et al.,1993), or two injections of relativistic SCR during the event (Torsti et al., 1991). Our analysis extends the previous results and demonstrates some new details that may help understanding this very complicated GLE. For instance, our study showed that anisotropy characteristics were quite different at the time of the first and second injections. Namely, during the first, rigid injection the anisotropy was unidirectional and pointing out of the Sun. And during the second, soft injection, the anisotropy was bidirectional showing maximal intensity in the opposite directions of the anisotropy axis.

DATA ANALYSIS

Two Component Structure of SCR flux

Fig.1 shows characteristic SCR intensity profiles at four NM stations and demonstrates existence of two distinct and shifted in time injections (Vashenyuk et al.,1993). Namely, the impulselike profile of Alma-Ata NM shows the first, prompt and rigid injection in the event. And Mirny station shows the second soft and delayed injection. Goose Bay station shows two maxima, one of which seems to be caused by the first injection because it nearly coincides in time with the Alma-Ata profile. And

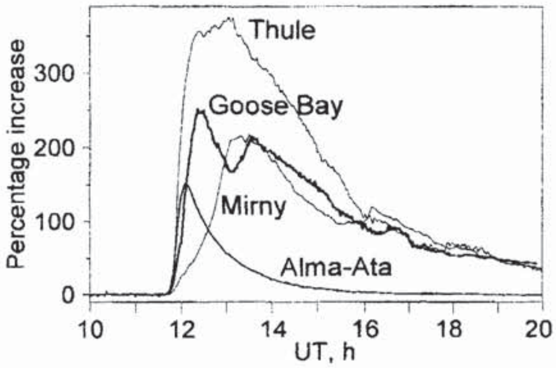

Fig. 1. Intensity profiles at different neutron monitor stations during the September 29, 1989 GLE.

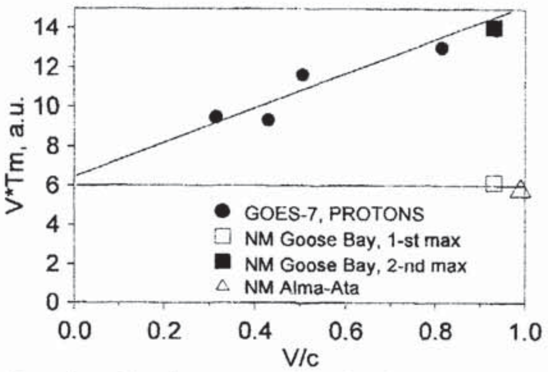

Fig. 2. $v{\cdot}T_m$ *diagrams for the September 29, 1989 GLE.*

the second maximum seems to be formed by the second injection because it coincides with the delayed profile of Mirny. The flat maximum of Thule profile is perhaps a result of summation of decreasing prompt and increasing delayed injections (Vashenyuk and Miroshnichebko, 1997). Existence of two SCR components in the 29.09.1989 GLE can be revealed also from the vT_m diagrams (Fig.2). Reinhard and Wibberenz (1974) showed that the whole path traveled by the main bulk of solar particles constituting the intensity maximum, $v{\cdot}T_m$ may be expressed with the sum of interplanetary A_m and coronal $B_m{\cdot}v$ parts of this path:

$$v{\cdot}T_m = A_m + B_m{\cdot}v \tag{1}$$

where v is the velocity of particles, T_m is the time from the moment of generation to the maximum of intensity, A_m is the summary interplanetary path and B_m is the time delay of the particles in the corona. It is seen that experimental points in Fig.2 form two linear dependencies of type (1).One of them, with great inclination, unites data of nonrelativistic solar protons measured by the GOES-7 spacecraft and the second maximum measured by the NM Goose Bay. All these particles belonged obviously to the same population which was delayed in the corona and than released simultaneously through the same time B_m Another possibility is a simultaneous acceleration of the DC particles of by some acceleration mechanism at the posteruption phase of the flare. The second straight line nearly parallel to the horizontal axis is drawn through the points corresponding to the intensity maximum on the Alma-Ata NM profile and the first maximum on the NM Goose-Bay. So the prompt component of SCR is represented by the relativistic protons only (Bazilevskaya and Vashenyuk, 1981). This has been confirmed also by the specific form of rigidity spectrum with a cutoff at low rigidities (Cramp et al., 1993). Such a quasiexponential form of the spectrum is characteristic for the mechanism of acceleration during processes of magnetic merging in the solar corona (Perez-Peraza et al., 1991). On the other hand, the rigidity spectrum of the delayed population in the event (the second maximum on the NM Goose Bay and the straight line with a great slope in Fig.2) corresponds to the mechanism of stochastic acceleration (Gallegos-Cruz and Perez-Peraza, 1995) as it has been shown by Miroshnichenko et al. (1995).

Anisotropy Effects

Fig. 3 shows asymptotic directions in the solar-ecliptic coordinates for a number of NM stations drawn on the tables by Gall et al., (1982) The coordinate center is the direction to the Sun and positions of the asymptotic cones correspond to 13 UT. The anisotropy axis at the beginning of the event passed through the Thule asymptotic cone (Smart et al., 1991), and so perhaps, was directed the IMF: about 60 deg. to the West from the Earth-Sun line (the garden-hose direction) and inclined to the ecliptic at the angle of ~50 deg. It is seen from the Figure that the asymptotic cone of Mirny station is pointed nearly opposite to the anisotropy vector. So this station as well as the pair of Apatity and Oulu neutron monitors accepted radiation from the antisun direction. The asymptotic

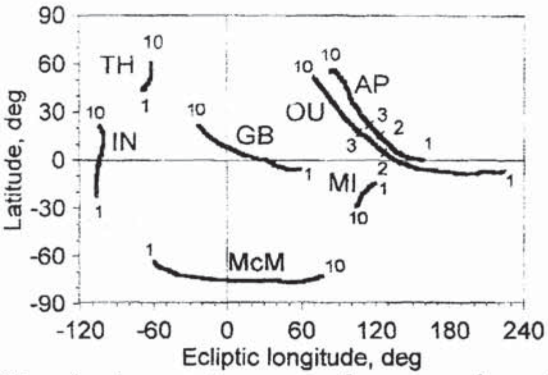

Fig. 3. Asymptotic cones for a number of neutron monitors (Thule, Inuvik, McMurdo, Goose Bay, Mirny, Oulu and Apatity) at 13 UT 29.09.1989.

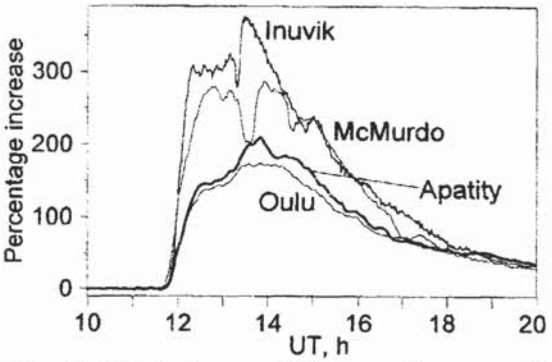

Fig. 4. The intensity difference between the closely spaced Apatity and Oulu stations indicating the possible sunward anisotropy during the second increase.

cone of the Goose Bay station was stretched nearly along the anisotropy axis. So the first intensity maximum at this station was caused by the PC particles coming through the high rigidity part of asymptotic cone adjacent to the cones of the Thule and Inuvik stations looking at the Sun. The second intensity maximum at the Goose Bay station was caused by the DC of SCR which should have arrived via the low rigidity part of asymptotic cone, adjacent to the cone of Mirny, looking out of the Sun. The anisotropic character of the sun-directed flux during the second increase is demonstrated in Fig.4 .

The remarkable detail here is the difference in intensities between the closely spaced neutron monitor stations Apatity and Oulu just during the second increase. The similar situation was observed during the 7.05.1978 GLE (Shea and Smart, 1982). As was shown in the paper Apatity and Oulu stations have close asymptotic directions at high rigidities and rather spaced at low ones. So an anisotropic flux of solar particles with a soft energetic spectrum may cause the difference in intensities between Apatity and Oulu stations. The second injection in the 29.09.1989 GLE was rather soft (Smart et al., 1991) and the observed difference in intensities between the Apatity and Oulu stations may denote that the sunward SCR flux was anisotropic. Because the sunward looking Thule and Inuvik stations registered the second increase with an equal effectively as the looking back Mirny station we may conclude that the DC radiation had the bidirectional anisotropy. The bidirectional anisotropy usually is an indication of magnetic loop structure (Palmer et al., 1978, and many others). So one can suppose that during the 29.09.1989 GLE in the IMF existed a large-scale, loop-like structure both ends of which were rooted into the Sun.

DISCUSSION

The similar 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 can give the following interpretation of the phenomenon. The first rigid and prompt injection in the 29.09.1989 GLE proceeded during the impulsive phase of the flare (Vashenyuk, and Miroshnichenko, 1997) which was close to the start of type II radioburst or the first

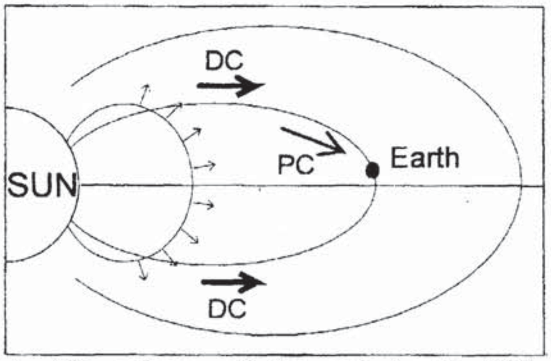

Fig. 5. The scheme of the anisotropic SCR propagation in the meridianal plane (out of scale). PC is the prompt component, DC is the delayed component of SCR. The possible source of the DC in the solar corona is shown.

significant maximum of the microvawe emission (Cliver et al., 1982). The first injection was very anisotropic and unidirected with the anisotropy axis passed through the Thule asymptotic cone. The underground telescopes (UT) showed an increase only in the northern hemisphere: Embudo NM, USA (Swinson and Shea, 1991) and Yakutsk, Russia (Krymsky et al., 1990). UT at Hobart registered no increase while the NM Hobart showed the effect of 288 percent as its asymptotic cone elongated into the north hemisphere (Gall et al., 1982). The second gradual ejection could be related obviously with a CME (Kahler, 94). Because this kind of ejection should proceed over a wide area occupied by the expanding coronal disturbance or CME, one cannot exclude a possibility that the SCR could be injected into the two legs of large-scale loop rooted into the solar corona. This situation is shown schematically (out of scale) in Figure 5. The earth is inside the large-scale looped structure of IMF, which could be created by the preceding CME eruptions. The prompt particles presumably generated in the localized 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 or acceleration 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.

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