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Unexpected burst of solar activity recorded by neutron monitors during October–November 2003

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Abstract

During the extreme burst of solar activity in October–November 2003, a series of outstanding events distinguished by their magnitude and peculiarities were recorded by the ground based neutron monitor network. The biggest and most productive in 23rd solar cycle active region 486 generated the most significant series of solar flares among of which the flare X28/3B on November 4, 2003 was the mostly powerful over the history of X-ray solar observations. The fastest arrival of the interplanetary disturbance from the Sun after the flare event in August 1972 and the highest solar wind velocity and IMF intensity were observed during these events. In one-week period three ground level enhancements (GLEs) of solar cosmic rays were recorded by neutron monitor network (28, 29 October and 2 November 2003). Maximum proton energy in these events seems to be ranged from 5 to 10 GeV. Joint analysis of data from ground level stations (neutron monitors) and satellite measurements allows the estimation of the particle path length, the onset time of the injection on the Sun and some other proton flux characteristics.

Keywords: Ground level enhancement; Solar cosmic rays; Neutron monitors

1. Introduction

Solar cosmic rays (SCR) can effectively be used for studying the processes of particle acceleration in the solar atmosphere and their propagation in interplanetary space, as well as for understanding the electromagnetic conditions at the Sun. On rare occasions a solar flare will accelerate protons to sufficiently high energies for these particles to propagate along the heliomagnetic field to the earth and be detected as a sharp increase in the counting rate of a ground based cosmic ray detector. Such events are known as ground level enhancements (GLEs). Since 1942 there have been recorded 67 GLEs by neutron and muon monitors.

An unusual burst of solar activity in October–November 2003 resulted in series of outstanding events recorded by ground based neutron monitor (NM) detectors. In a 6-days time period NM network recorded three GLEs of solar cosmic rays: on 28 October (GLE 65, also known as the "Greek effect"), on 29 October (GLE66) and on 2 November (GLE67). In the present work, we examine the time profiles of the observational variations of CR intensity at multiple sites, in a wide energy range, in order to allow the determination of the *amplitude*, the *onset time* and the *maximum energy* reached for each one of these three events. Data from several NM stations of the worldwide network (Fig. 1) are used. Moreover, for GLE 65 the onset time of the injection of the accelerated particles from the sun and

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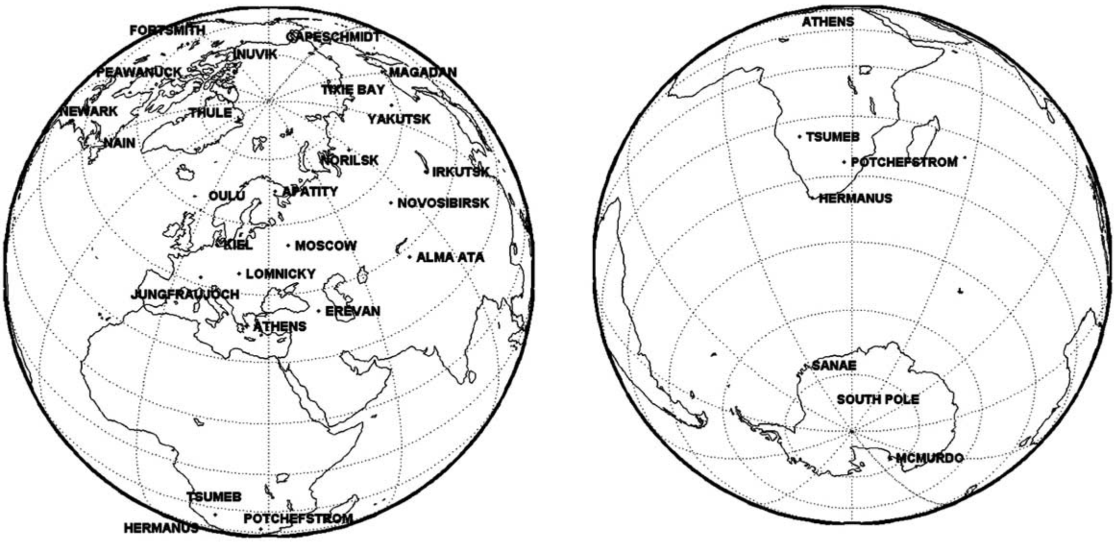

Fig. 1. Neutron Monitor stations of the worldwide network used in our analysis.

the length of their path in the interplanetary space is calculated.

2. Solar activity in October–November 2003

The sunspot number maximum of solar cycle 23 occurred in April 2000, while a secondary maximum was seen during the period September 2001–February 2002 (Coffey and Erwin, 2002). Therefore, year 2003 falls into the descending phase of the current solar cycle.

From mid-June until mid-October 2003 solar activity was relatively low: big or complicated active regions were absent. The situation changed in the second half of October with the appearance of sunspot group 484 on the eastern solar limb. On 19 October, this group started to generate big flares having already taken delta configuration of magnetic field. On 23 October another sunspot group (486), bigger and more dangerous (as it was located near the central meridian of the Sun), appeared on the visible part of the solar disk and started to generate series of great flares. The most important flares (>M4) generated by sunspot groups 484 and 486 in the period 19 October–5 November are presented in Table 1. It is clearly seen that sunspot group 486 generated 13 major flares (seven of them were very powerful, i.e. >X1), turning out to be the most productive sunspot group in the 23rd solar cycle. In the last days of October

Table 1
A list of the greatest flares (>M4) in October–November 2003 is given

Date	Sunspot group	T_1 (UT)	T_2 (UT)	T_3 (UT)	Location	Importance	Class
19/10/2003	484	16:29	17:04	16:50	N08 E58	1N	X1.1
22/10/2003	486	19:47	20:28	20:07			M9.9
23/10/2003	486	08:19	08:49	08:35	S21 E88	1B	X5.4
23/10/2003	486	19:50	20:14	20:04	S17 E84	1N	X1.1
24/10/2003	486	02:27	03:14	02:54	S19 E72	1N	M7.6
24/10/2003	486	05:04	05:16	05:10	S24 E74	1F	M4.2
26/10/2003	486	05:57	07:33	06:54	S15 E44	3B	X1.2
26/10/2003	484	17:21	19:21	18:19	N02W38	1N	X1.2
26/10/2003	484	21:34	21:48	21:40	N01W38	2N	M7.6
27/10/2003	486	09:21	09:32	09:27	S16 E26	SF	M5.0
27/10/2003	486	12:27	12:52	12:43	S17 E25	SF	M6.7
28/10/2003	**486**	**09:51**	**11:24**	**11:10**	**S16 E08**	**4B**	**X17.2**
29/10/2003	**486**	**20:37**	**21:01**	**20:49**	**S15W02**	**2B**	**X10.0**
2/11/2003	**486**	**17:03**	**17:39**	**17:25**	**S14W56**	**2B**	**X8.3**
3/11/2003	488	01:09	01:45	01:30	N10W83	2B	X2.7
3/11/2003	488	09:43	10:19	09:55	N08W77	2F	X3.9
4/11/2003	486	19:29	20:06	19:50	S19W83	3B	X28
5/11/2003	486	10:46	10:56	10:52	S16W90	SF	M5.3

T_1 is the time the detectors on GOES-10 started to record increase in the radiation flux, T_2 is the time the values of the radiation flux returned to the level preceding the event and T_3 is the time of maximum radiation flux. The time of emission of radiation (i.e., the real start time of the flare on the sun) is found by subtracting 8 min from T_1.

several new quickly evolving sunspot groups appeared too. During a two-weeks time period (15–29 October) the sunspot number increased (for the first time in solar cycle 23) 13 times. On 28 October, the situation on the Sun is very rare: three giant sunspot groups, competing in activity, were simultaneously located on the visible part of the solar disk. Large fluxes of accelerated particles followed the flares of 28, 29 October and 2 November. On 4 November, group 486 generated the biggest flare ever detected: X28/3B.

3. Cosmic-ray variations

During the first 20 days of October no significant variations of galactic cosmic ray flux were observed. An extreme magnetic storm started on 21 October and was followed by series of Forbush effects appearing after sudden storm commencements (SSC) on 24, 26, 28, and 29 October and indicating the possible presence of interplanetary shocks (Fig. 2). In some stations, the decrease reached ~25% (e.g., Oulu, Moscow). Athens NM (cut-off rigidity: 8.53 GV) recorded for the first time in its history of operation a decrease of about 20%. A recovery of the great Forbush decrease started on 29 October but was slowed down by SSC on 4 November. Powerful flares by sunspot group 486 on 28, 29 October and 2 November caused particle acceleration resulting in ground level enhancements recorded by neutron monitors.

All GLEs in October–November 2003 were large enough and had strong and long lasting *anisotropy* with dominating southern fluxes. Maximum amplitudes of the CR variations due to the arrival of solar particles were observed by NMs located at the southern hemisphere, in all three cases. Time profiles of the CR variations during these three events were different due to different interplanetary and geomagnetic conditions. Especially in case of GLE 66 (on 29 October) there was unusual interplanetary disturbance, severe magnetic storm and a giant Forbush effect.

The *onset time* of the ground level event on 28 October was 11:12:30 UT. The maximum amplitude of CR variations was recorded by Mc Murdo NM station at ~11:52:30 UT and was ~(44.7 ± 3.2)%. The intensity–time profiles for GLE 65 as recorded by five NM stations are demonstrated in Fig. 3. The relevant parameters (geographic coordinates, altitude, geomagnetic cut-off rigidity) of the stations that did or did not record this enhancement, as well as the onset time, the amplitude of the CR variations and the time that it was observed, for each station, are presented in Table 2. Prior to the onset of the enhancement, a few NM stations recorded *spikes* in the data. The amplitude of these '*precursors*' and the time they appeared at each station are presented in Table 3. Precursors were also observed during the GLE of September 29, 1989 (Takahashi et al., 1990; Alessio et al., 1991). A few researchers have suggested that the observed effect was due to very high-energy protons or prompt solar neutrons, but as far as we know, these findings have not been interpreted adequately up to now (Miroshnichenko et al., 2000). It is remarkable that although a precursor was clearly observed at 10:32:30 UT, no GLE was registered in Athens NM on October 28, 2003.

Another peculiar feature noticed during GLE 65 was the existence of two far-distanced maxima in the data of some high latitude NM stations. In Fortsmith NM station, the first maximum was observed at 13:02:30 UT (9.2 ± 0.7%), whereas the second one was observed at 17:27:30 UT (12.0 ± 0.9%). Inuvik NM station also recorded two maxima: at 11:42:30 UT (10.5 ± 0.9%) and at 19:17:30 UT (10.2 ± 0.9%). In Nain NM station, the first maximum was observed at 12:02:30 UT (7.3 ± 0.6%) and the second at 19:47:30 UT (10.1 ± 0.8

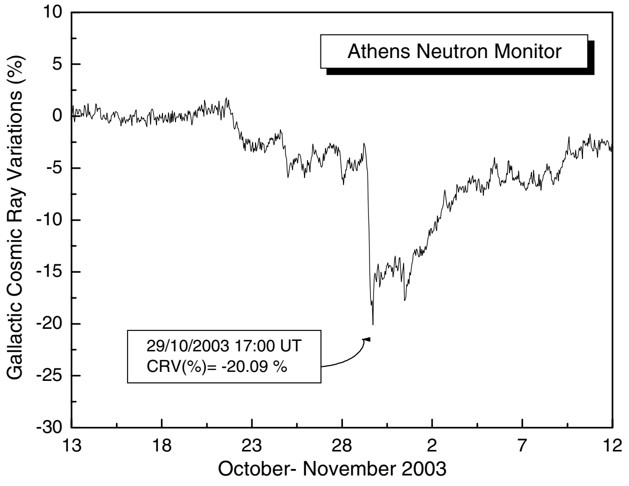

Fig. 2. Great Forbush effect in October–November 2003 recorded by Athens NM station.

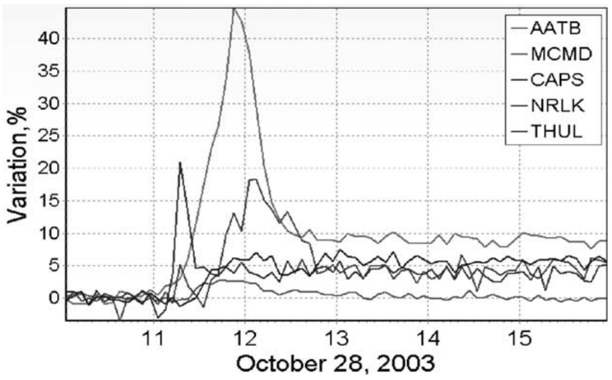

Fig. 3. GLE 65 as recorded by five NM stations (AATB = Alma-Ata (B), MCMD = McMurdo, CAPS = Capeschmidt, NRLK = Norilsk, THUL = Thule).

Table 2
Onset time, maximum % increase and time of maximum for GLE 65, as observed by each NM station

NM Stations		Cut-off rigidity (GV)	Geograph. latitude (°)	Geograph. longitude (°)	Altitude (m)	t^{i}_{on}(UT)	Maximum amplitude (%)	$t^{i}_{\max}$ (UT)
Polar stations	McMurdo	0.01	−77.95	166.6	48	11:12:30	44.7 ± 3.2	11:52:30
	Barentsburg	0.05	78.12	14.42	0	11:42:30	9.2 ± 1.4	14:12:30
	Thule	0.1	76.6	−68.8	260	11:32:30	7.5 ± 0.6	13:02:30
	South Pole	0.11	−90	0	2820	11:17:30	17.1 ± 1.2	12:02:30
	Inuvik	0.18	68.35	−133.72	21	11:27:30	10.5 ± 0.9	11:42:30
	Fortsmith	0.3	60	−112	0	11:27:30	9.2 ± 0.7	13:02:30
	Nain	0.4	56.6	−61.7	0	11:32:30	7.3 ± 0.6	12:02:30
	Capeshmidt	0.45	68.92	−179.47	0	11:17:30	18.4 ± 2.2	12:07:30
	Peawanuck	0.5	55	−85	0	11:37:30	8.6 ± 0.7	12:17:30
	Norilsk	0.63	69.26	88.05	0	11:12:30	21.0 ± 2.1	11:17:30
	Apatity	0.65	67.55	33.33	177	11:32:30	7.5 ± 0.6	13:47:30
	Sanae	0.73	−71.7	−2.85	856	11:32:30	11.1 ± 1.1	12:12:30
	Oulu	0.81	65.02	25.5	0	11:42:30	7.7 ± 0.8	11:52:30
	Yakutsk	1.7	62.02	129.72	105	11:22:30	9.7 ± 3.2	12:02:30
	Newark	1.97	39.7	−75.7	50	11:22:30	7.8 ± 1.0	12:27:30
Mid-latitude stations	Magadan	2.1	60.1	151	0	11:22:30	9.6 ± 0.9	11:57:30
	Kiel	2.29	54.3	10.1	54	11:17:30	8.5 ± 0.8	11:27:30
	Moscow	2.46	55.47	37.32	200	11:17:30	9.1 ± 0/8	11:27:30
	Irkutsk	3.66	52.1	104	433	11:32:30	8.2 ± 0.7	11:52:30
	Irkutsk-2	3.66	52.28	104.02	2000	11:12:30	9.2 ± 0.8	11:42:30
	Irkutsk-3	3.66	52.28	104.02	3000	11:17:30	8.50.5	11:47:30
	Lomnicky Stit	4	49.11	20.13	2634	11:17:30	7.3 ± 0.4	11:17:30
Low latitude stations	Jungfraujoch	4.48	46.55	7.98	3550	11:17:30	3.1 ± 0.2	11:17:30
	Jungfraujoch1	4.48	46.55	7.98	3550	11:17:30	3.3 ± 0.4	11:32:30
	Hermanus	4.9	−34.42	19.22	26	11:17:30	3.2 ± 0.4	12:52:30
	Alma Ata	6.69	43.14	76.6	3340	11:27:30	2.7 ± 0.3	11:42:30
	Potchefstrom	7.3	−26.68	27.92	1351	11:12:30	2.80.5	11:27:30
	Erevan	7.6	40.5	44.17	2000	11:37:30	1.2 ± 0.5	11:57:30
	Erevan-3	7.6	40.5	44.17	3200	11:32:30	1.2 ± 0.3	11:47:30
	Athens	8.52	37.97	23.72	260	–	–	–
	Tsumeb	9.29	−19.2	17.6	1240	11:12:30	3.1 ± 0.2	11:12:30

Table 3
Spikes in CR data (precursors) on October 28, 2003

NM station	Cut-off rigidity (GV)	Geograph. latitude (°)	Geograph. longitude (°)	Altitude (m)	*T* (UT)	Spike (%)
Hermanus	4.9	−34.42	19.22	26	11:07:30	2.3 ± 0.3
Athens	8.52	37.97	23.72	260	10:32:30	3.7 ± 0.7
Tsumeb	9.29	−19.2	17.6	1240	11:07:30	3.4 ± 0.3

%). In Newark NM station, the first peak was observed at 12:27:30 UT (7.8 ± 1.0%), whereas the second one at 15:57:30 UT (7.7 ± 0.8 %). At last, Sanae NM recorded the first maximum at 12:12:30 UT (11.1 ± 1.1%) and the second one at 14:22:30 UT (11.7 ± 1.2%). Indications of a two-peak SCR increase at high latitude NMs were also reported during September 29, 1989 (Mathews and Venkatesan, 1990; Ahluwalia et al., 1991; Smart and Shea, 1991) and they were attributed the direction of the asymptotic cones of the station in relation to the direction of IMF (Smart and Shea, 1991).

Ground level enhancement on October 29 appears simultaneously with the beginning of the recovery phase after the great Forbush decrease that started on October 21, as it is shown in Fig. 4. A large magnetoshperic effect appearing during the last hours of 29 October (Fig. 4) causes additional increase in CR variations, which is clearly observed by neutron monitors located at mid/low latitudes. As a result, the definition of the exact increase in the observational variations of each NM station, is a subject of further analysis and study.

The onset time of GLE67 on 2 November was 17:17:30 UT (Fig. 5). The *maximum amplitude* of CR variations was recorded by South Pole NM station at ~17:52:30 UT and was about ~(36.0 ± 2.5)%. As in case of GLE 65, some precursors in the data of a few NM stations were observed too. Capeshmidt NM station re-

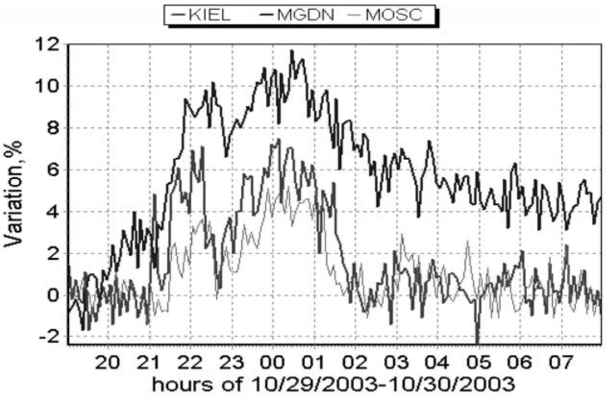

Fig. 4. GLE 66 on October 29 and large magnetospheric effect on 29–30 October (KIEL = Kiel, MGDN = Magadan, MOSC = Moscow).

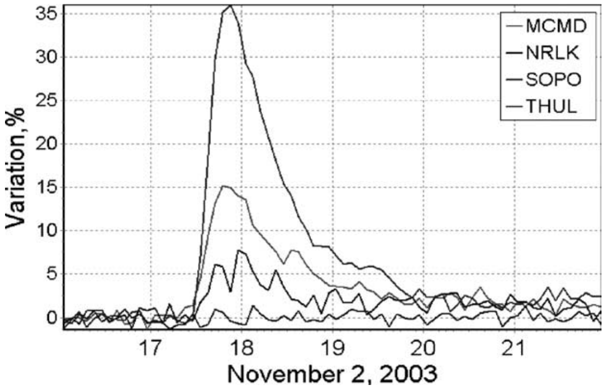

Fig. 5. GLE 67 as recorded by McMurdo (MCMD), Norilsk (NRLK), South Pole (SOPO) and Thule (THUL).

corded a spike in the data at 17:07:30 UT (2.2 ± 0.4%) and Yakutsk NM station recorded a precursor at 17:02:30 UT (2.5 ± 1.2%). At 17:07:30 Athens NM station recorded a precursor of the same amplitude as in case of GLE 65 (3.7 ± 0.7%).

4. Injection time of protons from the Sun

In solar flares, gamma-ray emission results from the interactions of fast particles with an underlying ambient medium. Gamma rays continuum at high energies is dominated by pion decay radiation. Pions (charged and neutral) are produced mostly in high energy (more than hundreds of MeV) via proton–proton and proton–α particle (Murphy et al., 1987). Thus the existence of gamma radiation with energy 60–70 MeV is evidence of energetic protons with energies more than 500 MeV.

The *time of injection* of protons with energy E from the Sun can be approximated from the observed rise time of the proton flux at 1 AU. If $t_{\mathrm{AU}}(E)$ is the onset of the increase in the proton flux at 1 AU, t_0 is the exact moment these protons were ejected from the sun, and $\tau(E)$ is the time of their flight from the Sun to the spacecraft (or to the surface of the earth), then we can write:

$$\tau(E) = t_{\mathrm{AU}}(E) - t_0 \text{ and } S = U_{\mathrm{rel}}(E)\tau(E),$$

where S is the path length from the proton release site on the Sun to the spacecraft and $U_{\mathrm{rel}}(E)$ is the relativistic velocity of protons with energy E. Of course, this approximation assumes that all particles were injected simultaneously from the Sun and they traveled the same path.

In our analysis 5-min resolution data from GOES-10 and NMs from the worldwide network are used. In case of NM data, we have chosen the data of only those stations that observed the earliest onset of the increase of the flux. These are the low latitude stations that record high energy particles on account of their high cut-off rigidity. The onset time of the flux-increase at 1 AU is identified by requiring $a \geqslant 2\sigma$ increase, as defined by the mean and standard deviation preceding the event. Gamma-ray high-energy emission started at about 10:56 UT and lasted until 10:59 UT, as defined by the data from CORONAS-F satellite. Using the method of linear regression one can define the path length S in the interplanetary space of the particles and the injection time t_0 on the Sun. Our result gave

$$t_0 = (10:56:30 \pm 00:03:54) \text{ UT and}$$
$$S = (3.04 \pm 0.47) \cdot 10^{13} \text{ cm.}$$

As one can see, the onset of gamma-emission coincided with the calculated injection-time. This fact may be evidence of the nature of the acceleration mechanism, which in this case seems to be the flare itself.

5. Discussion and conclusions

From the above analysis some interesting results are obtained:

(1) During each one of the three ground level enhancements in October–November 2003 NM stations with low cut-off rigidities recorded, in general, larger % increases in the observed flux than those with higher ones. This is dependent from the cut-off rigidity (R_c) that characterizes a NM station corresponds to the minimum energy (threshold) a primary particle should have in order to result in the increase of the CR flux recorded by this certain neutron monitor. Therefore stations with low cut-off rigidities cover bigger part of the CR spectrum and they accept more particles covering a wider range of energies than stations with higher ones.

(2) Among neutron monitors having similar cut-off rigidities, located in the same place (or in places with similar geographical longitudes), those located at higher altitudes recorded larger percented variations. For example during GLE 65 the maximum amplitude of

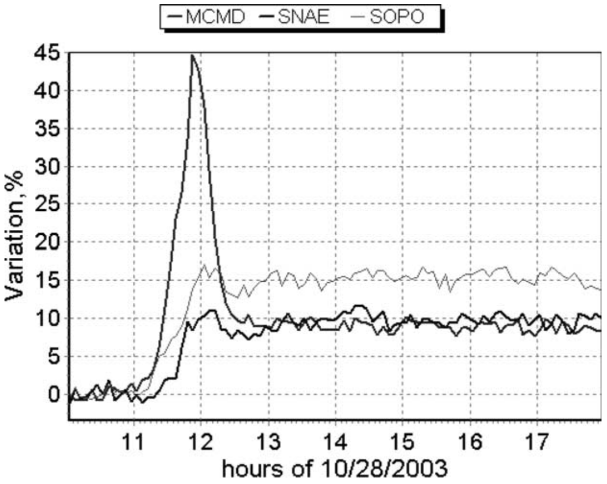

Fig. 6. Evidence of anisotropy during GLE65 as recorded by the stations: McMurdo (MCMD), Sanae (SNAE) and South Pole (SOPO).

the CR variations recorded by the NM in South Pole ($R_c = 0.11$ GV, long. = 0°, alt. = 2820 m) was (17.1 ± 1.2)%, whereas for Sanae NM ($R_c = 0.73$ GV, long. = − 2.85°, alt. = 856 m) it was (11.1 ± 1.1)%. Moreover, NM stations Irkutsk (long. = 104°, lat. = 52.1°, alt. = 433 m) and Irkutsk-3 (long. = 104.02°, lat. = 52.28°, alt. = 3000 m), characterized by the same cut-off rigidity and differing slightly in geographical coordinates, observed different fluxes too, during GLE 65. The difference is attributed to the absorption of nucleons by the atmospheric layer between these two sites (Ahluwalia and Xue, 1993).

(3) Stations of the same cut-off rigidity, differing strongly in longitude recorded different fluxes during GLE 65 indicating the existence of anisotropy in solar cosmic rays' arrival. This observed difference in CR variations cannot always be attributed to altitude. For example McMurdo station ($R_c = 0.01$ GV, long. = 166.5°, alt. = 48 m) recorded larger flux increase than South Pole ($R_c = 0.11$ GV, long. = 0°, alt. = 2820 m), although the latter is located much higher. Moreover if there were no anisotropy present NM stations of the same cut-off rigidity, at the same altitude, differing in longitude should reveal identical time-profiles during GLE65. Fig. 6 provides striking evidence of a significant anisotropy during this GLE.

(4) The time at which solar energetic particles are injected from the Sun and their path in the interplanetary space are important clues to the site and nature of the particle's acceleration mechanism. In case of GLE65, the flare mechanism seems to be responsible for the particles acceleration. The path the particles traveled is ~1.8 times bigger than the length of the archemedian magnetic field line. This may be evidence of interplanetary scattering by magnetic field irregularities, or anisotropic particle emission and propagation.

Further study of these extreme events will lead to better understanding of the coronal, interplanetary and terrestrial structures.

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References

Ahluwalia, H.S., Xue, S.S. Atmospheric attenuation length for relativistic solar protons. Geophys. Res. Lett. 20, 995–998, 1993.

Ahluwalia, H.S., Xue, S.S., Kavlakov, S.P. The ground level enhancement of September 29, 1989. In: Proc. 22nd Int. Cosmic Ray Conf., Dublin, vol. 3, pp. 93–96, 1991.

Alessio, M., Allegri, L., Fargion, D., Improta, S., Iucei, N., Parisi, M., Villoresi, G., Zangrilli, N.L. The ground level cosmic ray event of September 29, 1989, as recorded by the Rome detectors. Il Nuovo Cimento C 14, 53–60, 1991.

Coffey, H.E., Erwin, E.H. The curious behavior of the secondary maximum for solar cycle 23. In: 200th AAS Meeting, Bull. AAS, American Astronomical Society, vol. 34, p. 736, 2002.

Mathews, T., Venkatesan, D. Unique series of increases in cosmic ray intensity due to solar flares. Nature 345, 600–602, 1990.

Miroshnichenko, L.I., de Koning, C.A., Perez-Enriquez, R. Large solar event of September 29, 1989: ten years after. Space Sci. Rev. 91, 615–715, 2000.

Murphy, R.J., Dermer, C.D., Ramaty, R. High-energy processes in solar flares. Ap. J. Suppl. Ser. 63, 721–748, 1987.

Smart, D.F., Shea, M.A. A comparison of the magnitude of the 29 September 1989 high energy event with solar cycle 17, 18 and 19 events. In: Proc. 22nd Int. Cosmic Ray Conf., Dublin, vol. 3, pp. 101–104, 1991.

Takahashi, K., Wada, M., Sakamoto, E., Matsuoka, M., Munakata and Kohno, I. Observation of high energy solar particles on September 29, 1989, by neutron monitors with high time resolution. Proc. Jpn. Acad. Ser. B 66, 10–14, 1990.