Proceedings of ICRC 2001: 3558 © Copernicus Gesellschaft 2001

ICRC 2001

Forbush decrease on October 20-22, 1989: Solar protons, interplanetary and magnetospheric variations

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Abstract The Forbush decrease occurred on October 20, 1989 at the background of the ground level enhancement and was accompanied by the large geomagnetic storm. The Forbush decrease and the geomagnetic storm lasted about three days. During their recovery phase occurred another large GLE of October 22, 1989. Using independent data sets obtained by space, stratosphere and ground based detectors CR variations of solar, interplanetary and magnetospheric origin are separated for the Apatity and Moscow neutron monitors through this event.

1. Introduction

The Forbush decrease (FD) is a complex phenomenon, which may incorporate cosmic ray (CR) variations of interplanetary, geomagnetic and solar origin. The purpose of this work is to separate them for the Forbush decrease on October 20-22, 1989 .

The Forbush decrease of October 20, 1989 should reveal all types of CR variations. It started at the background of the ground level enhancement (GLE 43) of October 19, 1989 and another large GLE 44 occurred during its recovery phase on October 22, 1989. The strong shock wave driven by the coronal mass ejection (CME) from the solar flare of October 19, 1989 (25S 09E) caused large disturbances of the interplanetary space. The event was accompanied by the geomagnetic storm (SSC 09:16 UT, October 20, 1989), which leaded to dramatic changes in the cutoff rigidity at middle latitudes (by about 1.5 GV) according to results of the stratospheric experiment and the model estimates (see Struminsky and Lal, 2001 and references therein).

In order to understand mechanisms of particle propagation and acceleration in the heliosphere it is very important to study modulation processes in the energy range of about 1 GeV near the interplanetary shocks. Only in rare cases the energies of shock associated particles appears to be continuum from spacecraft to NM energies, as in the case of October 20, 1989 event. It may appear on the first look that the shock associated particles and the precursory increase have the same origin (Cane, 2000). However, it is not so on October 20, 1989 for several reasons.

These increases of CR intensity were separated in time and had different spectra. The precursor increase observed before arriving of the shock is a result of single reflection of galactic cosmic rays from the shock. The shock associated protons arrived after SSC and apparently were trapped near the shock. In order to explain such trapping of protons with $E > 100 MeV$ Bazilevskaya et al. (1994) assumed very small propagation mean free path $\lambda < 0.02 AU$. Another scenario is proposed below, two magnetic walls are clearly seen in the solar wind data, protons might be accumulated in this trap. A possibility of particle acceleration in the trap is discussed.

2. Data and Methods

In this work the CR variations observed on October 20-22, 1989 are studied using independent data sets obtained by space and ground based detectors. All necessary data were down loaded from the SPIDR database (http//spidr.ngdc.noaa.gov) and the home-page of Moscow NM (http//helios.izmiran.rssi.ru/cosray/main.htm).

Table shows some characteristics of NM stations used in this study.

Station	Long.	R_c^0, GV	N_0	Type
APTY	33.33	0.47	5924	18NM64
MOSC	37.32	2.43	7809	24NM64

Longitudes of these stations are nearly equal and they look in the same direction in the equatorial plane. The count rate averaged for eleven hours before the GLE onset on October 19, 1989, N_0, is taken as a reference level. Values of N_0 normalazed to 18NM64 differ by about 1.15%,

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apparently, this is a maximum possible geomagnetic variation in Moscow.
In general case the NM count rate in some particular time moment is proportional to

$$N \approx \int_{E_c}^{\infty} g(E,x) J(E) dE , \qquad (1)$$

where $g(E,x)$ - the NM sensitivity to primary cosmic rays, $J(E)$ - the differential energy CR spectrum, E_c - the current effective cutoff energy.
I have assumed for these estimates that the NM sensitivity $g(E,x) = 6.25 \cdot 10^{-9} E^{3.17}$ below 2000 MeV (Belov and Struminsky, 1997) and $g(E,x) = 0.0219 \cdot E^{1.15}$ above 2000 MeV (see Clem and Dorman, 2000 and references there in).
The effective cutoff energy E_c in Moscow was estimated for each hour of days October 20-21, 1989 by using hourly values of the *Dst* index and solar wind data (see Struminsky and Lal, 2001 and references there in).
If during quite time the effective cutoff energy is E_c^0 and the differential energy spectrum $J(E)_0$ is $J_0(E) = 2.1 \cdot 10^5 E^{-2.7} (cm^2 \cdot s \cdot sr \cdot MeV)^{-1}$ above 1650 MeV and $2 \cdot 10^{-5} (cm^2 \cdot s \cdot sr \cdot MeV)^{-1}$ below 1650 MeV, then the reference NM count rate would be

$$N_0 \approx \int_{E_c^0}^{\infty} g(E,x) J_0(E) dE . \qquad (2)$$

The chosen CR spectrum provides a reasonable difference between calculated counts rates of Moscow and Apatity NM's (1.25%).
The solar cosmic ray variations can be expressed by

$$\delta N_{sol} = \int_{E_c}^{E_{\max}} g(E,x) \delta J_{sol}(E) dE , \qquad (3)$$

where $\delta J(E)_{sol}$ is a spectrum of solar protons and $E_{\max}$ is their maximum energy.
Hourly average data from two integral channels of the GOES-7 proton detector were used to evaluate the spectrum of solar cosmic rays. These channels measured integral proton flux within 84-200 MeV and 110-500 MeV energy bands. Assuming the spectrum of solar protons in a form of power law function within 84-500 MeV interval one can estimate its power law index and normalizing constant from the observed ratio of channel count rates (Belov, Chertok and Struminsky, 1995). If the observed enhancement is really caused by this population of particles, then varying $E_{\max}$ for a given time moment it is possible to get the desired coincidence between observed and expected values of solar CR variations. In some cases the derived spectrum of solar protons appeared to be too soft and can not result in the observed increase.
An estimate for the geomagnetic variations is

$$\delta N_{geo} = \int_{E_c}^{E_c^0} g(E,x) J_0(E) dE , \qquad (4)$$

Because E_c likely would be in a range of allowed and forbidden trajectories called the cosmic ray peneumbra the integral (4) provides the upper limit of possible geomagnetic variations. The effect of penumbra should be considered carefully to get better accuracy of geomagnetic variations.
Removing the solar and geomagnetic CR variations we have interplanetary variations

$$\delta N_{\text{int}} = \delta N - \delta N_{sol} - \delta N_{geo} . \qquad (5)$$

Therefore, cosmic ray variations of different origin were separated in following steps:

- Estimates of cutoff rigidity changes;
- Estimates of NM count rate due to solar cosmic rays;
- Estimates of geomagnetic variations.
- Calculation of interplanetary variations.

3. Results and Discussion

3.1 Solar protons on October 20, 1989

The isotropic phase of the October 19, 1989 GLE's is used here to justify our ability to calculate a NM response to solar cosmic rays and, therefore, eliminate correctly the solar CR variations.
A reasonable coincidence between the observed and calculated NM count rates is achieved by varying the maximum energy of solar protons during the isotropic phase of the October 19, 1989 GLE. Figure 1 from top to bottom illustrates step by step the calculations of solar and interplanetary CR variations. In this sub-section changes of the cutoff energy were estimated using the modified *Dst* index (Struminsky and Lal, 2001). The corresponding geomagnetic variations are 0.75-1.25%.

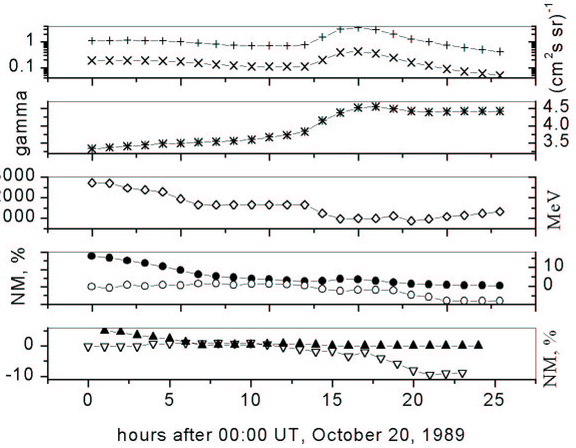

Fig.1 Proton flux within 84-200 and 110-500 MeV energy bands measured by the GOES-7 detector; a power law index of the proton differential energy spectrum deduced from the GOES data; a maximum energy of solar protons; interplanetary (open) and solar (black) CR variations of Apatity and Moscow NM's.

The spectrum deduced from the GOES data appeared to be too soft after 07:00 UT on October 20 to explain the pre-increase of 1-2% observed by middle and low latitude NM's. Therefore, this pre-increase should be caused by variations of the galactic CR spectrum $\delta J(E)_{\text{int}}$.

3.2 Forbush decrease on October 20-22, 1989

Figure 2 shows the GOES-7 proton data in linear scale; the modulation parameter $B \cdot V$, where B is the total IMF magnetic field strength and V is the solar wind velocity; the interplanetary variations of Apatity and Moscow NM's. The actual Forbush decrease and the increase of shock associated particles started at about 12 UT just after the first maximum of the $B \cdot V$ parameter. The Forbush pre-increase was obseved by NM's with highest rigidity, so its spectrum was very hard.

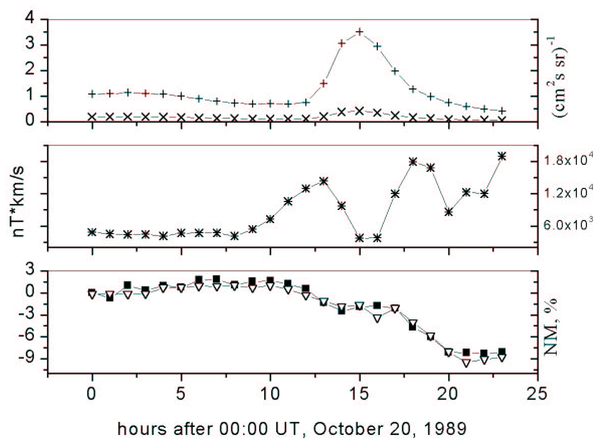

Fig.2 Proton flux within 84-200 and 110-500 MeV energy bands measured by the GOES-7 detector; the total IMP magnetic field strength (nT) multiplied by the solar wind velocity (km/s); variations of interplanetary origin registered by of Apatity (down triangle) and Moscow (dark square) NM's .

The precursor increase observed before arriving of the shock is a result of single reflection of galactic cosmic rays from the shock. The precursor increase lasted about seven hours (Fig. 2), so the propagation mean free path of CR protons down stream the shock is ~ 0.1 AU.
Contrary, the shock associated particles arrived after the shock and looked like trapped between two magnetic walls. The spectrum of shock associated particles deduced from GOES data was very soft. The first maximum of the $B_1 \cdot V_1 = 22.7nT \cdot 631km/s$ parameter was at 13:00 UT and the second $B_2 \cdot V_2 = 22.9nT \cdot 785km/s$ at 18:00 UT. A distance between the magnetic walls was ~0.09 AU at the Earth orbit and it was greater near the Sun. Apparently, this is a dimension of the magnetic trap and a mean free path of particles inside it.
The question is, were these particles injected into this region or they accelerated there (Struminsky, 2000) ? An average relative increase of particle energy as a result of one acceleration act (scattering from front and rear walls) would be

$$\beta = 1 + \frac{4}{3}\frac{V_2 - V_1}{c} = 1 + 6.8 \cdot 10^{-4},$$

a number of possble acceleration acts is

$$k = T \cdot c / \lambda = 1920,$$

where $T \approx 24 hours$ is a propagation time of the magnetic trap to Earth .
Initial energy of particles might increase by a factor of $\beta^k = 3.68$ inside the trap on its way to Earth.
Figure 3 shows variations of Moscow NM count rate and their contributions due to geomagnetic and interplanetary effects during the Forbush decrease. The solar CR variations were negligible at that time. Because solar wind data are not available for this period the normal Dst index has been used for estimates of the cutoff energy. An error for the geomagnetic variations is about 0.5%.
Because solar wind data for October 21, 1989 are not available the nature of the FD second step is not clear. Hofer and Fluckiger (2000) by the example of the March 24, 1991 FD demonstrated the potential of NM data to investigate complex interplanetary structures. Possibly, an applying of the same technique may help to resolve this problem.

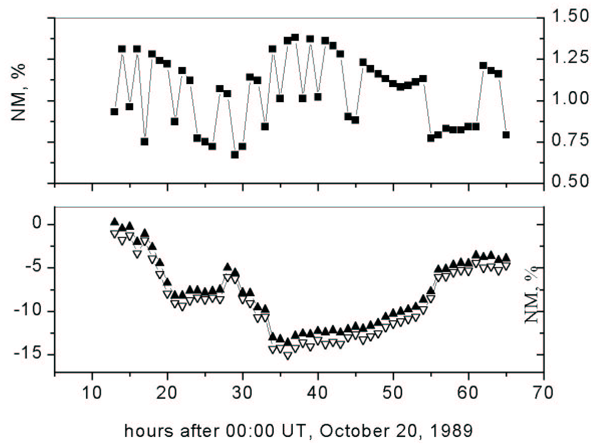

Fig. 3. Variations of Moscow NM count rate (up triangles), their contributions due to geomagnetic (squares) and interplanetary (down open triangles) variations.

3.3 Solar protons on October 22, 1989

The GLE on October 22, 1989 started at time, when the CR depression was still considerable, so the hourly count rates at 17:00 were taken as a reference level N_0. Figure 4 from top to bottom illustrates step the calculations of solar CR variations for this event.
The initial phase of the October 22, 1989 GLE was highly anisotropic and had a complex temporal structure with several significant peaks implying multiple particle injection or varying interplanetary propagation conditions. This explains the difference between observed (9.5%) and

expected (20%) variations of the Apatity NM . At that time the GOES-7 satellite was on the day side, but the Apatity NM was on the night side. The maximum NM enhancement observed by day-side high latitude NM ' is 19.5 %. The GOES proton detector is sensitive to the large CR anisotropy.
Some discrepancy between the observed and calculated variations of Apatity NM during the late phase was caused by changing CR background during the FD recovery phase.

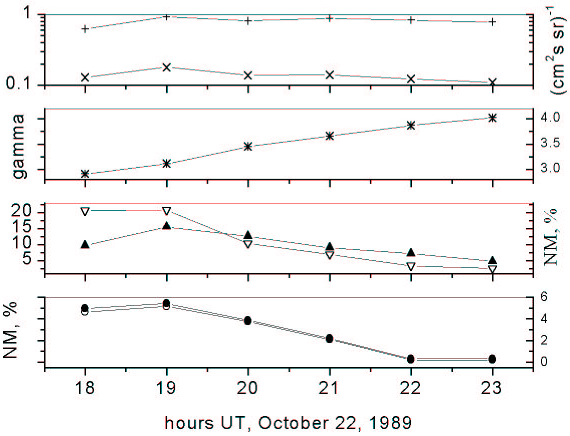

Fig. 4. Proton flux within 84-200 and 110-500 MeV energy bands measured by the GOES-7 detector; a power law index of the proton differential energy spectrum deduced from the above data; variations of Moscow and Apatity NM count rates (open) and their part due to solar cosmic rays (black).

4. Summary

Cosmic ray variations of different origin have been separated for the October 20-22, 1989 Forbush decrease in data of the Apatity and Moscow neutron monitors.
The cut-off rigidity was changing significantly through the event at middle latitudes, however, the corresponding geomagnetic variations estimated for the Moscow NM were less than 1.5 %.
Solar cosmic ray variations deduced from the GOES-7 proton data show a reasonable agreement with NM variations observed during isotropic phases of corresponding GLE.
The large anisotropy during the beginning of the October 22, 1989 GLE , which is well known according to NM data, reveal itself in the GOES data as well.
The Forbush pre-increase and the shock associated enhancement of lower energy particles have been separated in time. The Forbush pre-increase had a very hard spectrum, the maximum energy of modulated protons was tens GeV. The shock associated enhancement had a soft spectrum with maximum energy less than 1 GeV. The last particles caused only small increase of polar and middle latitude NM count rate. The enhancement at middle latitude NM was observed only owing to changes of the cut-off rigidity. Therefore, these enhancements are caused by different populations of particles.
The shock associated particles were trapped between two magnetic walls. These particles were accelerated close to the Sun, the initial energy of injection might increase by a factor of four only on the way to Earth.

Acknoledgments The author thanks the staff of IIG and, in particular, the staff of Equatorial Geophysical Research Laboratory for their help and hospitality during his stay in India. He also thanks the DST of Indian Government for providing the ILTP fellowship. This work was partly supported by the Russian Federal Program "Astronomy" and Russian Foundation for Basic Research (grants 99-02-18003 and 01–02-17580).
The author is grateful to all researchers provided their data to the Space Physics Interactive Data Resource.

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