Annales Geophysicae (2002) 20: 1247–1252 © European Geophysical Society 2002

Letter to the Editor

Forbush precursory increase and shock-associated particles on 20 October 1989

A. Struminsky

Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation (IZMIRAN), Troitsk, Moscow Reg., 142092, Russia, and Equatorial Geophysical Research Laboratory, Indian Institute of Geomagnetism, Krishnapuram, Tirunelveli 627011, India

Received: 4 July 2001 – Revised: 9 January 2002 – Accepted: 10 March 2002

Abstract. Strong interplanetary disturbances may affect cosmic ray protons tremendously with energies less than 1 GeV, increasing their intensity by hundreds of percents, but they are not so effective for protons of higher energies. This energy limit is crucial to understand processes of cosmic ray propagation and acceleration in the heliosphere. The Forbush pre-increase and the effect of shock-associated particles observed on 20 October 1989 illustrate the problem. This is a rare event, when the energies of shock-associated particles measured by the GOES-7 satellite spread continuously to the neutron monitor energies. The Forbush pre-increase could be attributed to a single reflection of galactic cosmic rays from the magnetic wall observed at 12:00 UT. It had a very hard spectrum with maximum energy of modulation more than 10 GeV. The spectrum of shock-associated particles was soft and their maximum energy was less than 1 GeV. The problem of shock acceleration versus trapping is discussed for the 20 October 1989 event. It is argued that the shock-associated particles were accelerated near the flare site and then propagated to the Earth inside the trap between two magnetic walls at 12:00 UT and 17:00 UT.

Key words. Interplanetary physics (cosmic rays; energetic particles; interplanetary magnetic fields)

1 Introduction

The proton energy of about 1 GeV corresponds to the upper energy limit of satellite detectors and the lower energies of cosmic rays (CR) accessible by the neutron monitor (NM) network. Knowing details of modulation processes in this energy range, where the scale of modulation processes may differ tremendously, is very important to understand mechanisms of particle propagation and acceleration in the heliosphere. Several percents are characteristic for CR variations observed by NMs, but satellite detectors might register variations of several orders simultaneously. Therefore, direct comparison of data sets obtained by NMs and particle detectors aboard satellites may clarify some physical limits of the modulation processes in the heliosphere.

A passage of interplanetary shock is associated with two distinct effects in CR, one is the Forbush decrease observed by ground-based detectors and the other is the enhancement of lower energy CR in the interplanetary space. The last effect is often attributed to particle acceleration by interplanetary shocks and researchers refer to such increases as shock-accelerated particles. However, an ability of interplanetary shocks to accelerate protons for energies more than several MeV has not been proved yet (Lim et al., 1995; Kallenrode, 1997). In addition, CR particles can be simply trapped near the shock. I think that it would be more accurate to call them the shock-associated particles.

Many Forbush decreases have a precursory increase, which is observed several hours before the shock arrives , but only in rare cases do the energies of corresponding shock associated particles appear to be continuum from spacecraft to NM energies. A reflection of galactic cosmic rays from the magnetic wall, which may be separated from the shock, is generally considered as a possible model of the Forbush precursory increase. Cane (2000) proposed that both effects might be caused by the shock acceleration in such rare cases.

The solar activity in the NOAA active region 5747 on 18–19 October 1989, including the parent solar flare (25 S 09 E) of the ground level enhancement (GLE) of 19 October 1989 (the 43rd such event ever recorded, see the GLE database on http//helios.izmiran.rssi.ru/cosray/main.htm), caused large disturbances in the interplanetary space and the subsequent geomagnetic storm on 20 October 1989 (SSC 09:16 UT). The cutoff rigidity of cosmic rays changed dramatically at that time (Struminsky, 1992; Struminsky and Lal, 2001). Klein et al. (1999) reviewed neutral and charge particle emissions of the 19 October solar flare and provided evidences of prolonged energy release and particle acceleration during this event.

Correspondence to: A. Struminsky
(astrum@izmiran.rssi.ru)

The increase of shock-associated particles was detected by all energy channels of the GOES-7 proton detector on the background of the GLE 43 decreasing phase, with the maximum intensities even higher than those on 19 October 1989 during its main phase (a factor of 20 and 2 for the 8.7–14.5 and 110–500 MeV proton channels, respectively). The shock-associated particles were observed well after SSC (the first shock) and before the second discontinuity, which is visible in solar wind data at ∼17:00 UT. The Forbush precursory increase of 1–2% is clearly seen in data of low-latitude NMs before SSC. Apparently, cosmic ray variations of solar and geomagnetic origin masked the precursory increase and the effect of shock-associated particles in data of high- and middle-latitude NMs. Corresponding plots of cosmic ray variations registered by NMs are easily available on http//helios.izmiran.rssi.ru/cosray/main.htm. The purpose of this work is to investigate the effects of the shock-associated particles and the precursory increase on 20 October 1989 in data from the Apatity and Moscow NMs using independent data sets obtained by space and ground based detectors. In order to estimate the precursory increase for mid-latitude NMs the solar and geomagnetic CR variations should be removed from the total CR variations. The NM response to the shock-associated particles can be estimated using the same technique as for solar cosmic ray variations, accounting for changes in the geomagnetic cutoff.

The SMM coronagraph was not operating before 16:30 UT on 19 October, thereby leaving a large ambiguity in the identification of possible sources of the two interplanetary disturbances. In earlier papers (Bazilevskaya et al., 1994; Bavassano et al., 1994), the first shock was associated with the energetic 19 October solar event, so the second discontinuity should be attributed to the prolonged energy release during the decay phase of the flare. Note, that Cliver et al. (1990) first mentioned the second discontinuity and favored its association with the 19 October solar event. Cane and Richardson (1995) incorporated data of the 9–22 MeV proton intensity from the IMP-8 satellite, considering its enhancement at ∼17:00 UT as evidence of shock acceleration and, therefore, the existence of the second shock. They suggested that the second shock was more energetic than the first and so it is more likely to have been associated with the energetic 19 October solar event. In this case, in their opinion, another solar event on 18–19 October should be responsible for the first shock, but they did not find an obvious, unique association between the shock and a particular solar event. Moreover, the nature of the shock-associated enhancement on 20 October is not so obvious.

Bazilevskaya et al. (1994) argued that the shock-associated protons were apparently trapped in the region with a very small propagation mean free path $\gamma < 0.02$ AU behind the first shock. Another scenario for the shock-associated particles is proposed in this article. The solar wind data clearly show two magnetic walls, where solar protons accelerated near the flare site later might be trapped between these walls with a propagation mean free path $\gamma < 0.1$ AU.

Table 1. Characteristics of NM stations

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

2 Data and methods

In this work, the precursory increase and the effect of shock-associated particles observed on 20 October 1989 are studied using data obtained by different space and ground-based detectors. The method of data processing was used by Struminsky (2001) to separate CR variations of different origin. All necessary data were downloaded from the SPIDR database (http//spidr.ngdc.noaa.gov) and the home page of the Moscow NM.

Table 1 shows some characteristics of NM stations used in this study. Longitudes of these stations are nearly equal and they look in the same direction in the equatorial plane, so the effects of the CR anisotropy are negligible. The count rate averaged for eleven hours before the GLE onset on 19 October 1989, with N_0 taken as a reference level. Values of N_0 normalized to 18NM64 differ by about 1.15%. Apparently, this is a maximum value of possible geomagnetic variations in Moscow.

In the general case, the NM count rate in some particular time moment is proportional to

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

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. In this study, the NM sensitivity below 2000 MeV is assumed to be equal to $g(E,x) = 6.25\cdot 10^{-9}E^{3.17}$ and above this energy it is $g(E,x) = 0.0219\cdot E^{1.15}$. Values of the NM sensitivity above 3 GV are well known (see Clem and Dorman, 2000 and references therein). Belov and Struminsky (1997) estimated the NM sensitivity for lower rigidities from GLE data.

The effective cutoff energy, E_c, in Moscow was estimated for each hour on 20 October 1989 by the method of Flückiger et al. (1986), using the modified Dst index. The modified Dst index accounts for only the effects of the magnetospheric ring current and, therefore, should describe more properly changes in the cutoff rigidities (Struminsky and Lal, 2001). The reference NM count rate should be proportional

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

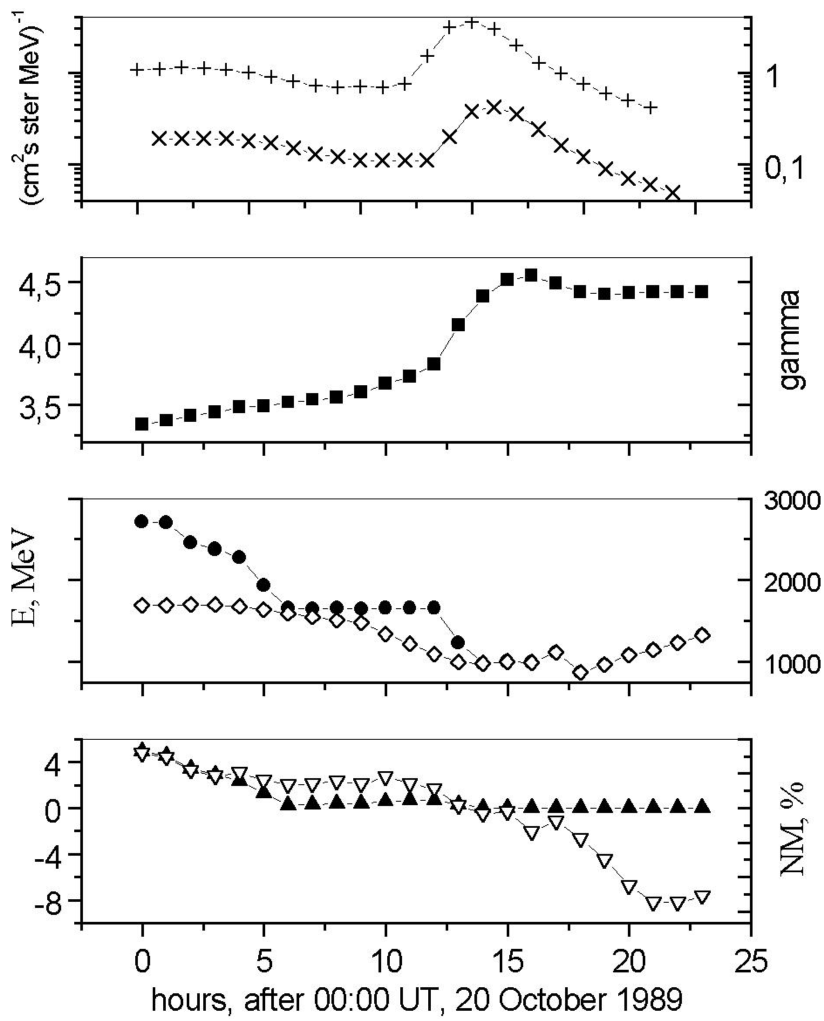

Fig. 1. Proton flux within 84–200 and 110–500 MeV energy bands measured by the GOES-7 detector; a power law index of the proton differential energy spectrum deduced from the above data; estimated values of the maximum energy of solar protons and the effective cutoff energy in Moscow; registered total (open down triangles) and estimated solar (black up triangles) CR variations for the Moscow NM.

where E_c^0 is an effective cutoff energy during geomagnetic quite periods and $J_0(E)$ is the differential energy spectrum of primary cosmic rays.

The undisturbed spectrum of primary CR in a power law form $J_0(E) = 2.1 \cdot 10^5 E^{-2.7}(\mathrm{cm^2 \cdot s \cdot sr \cdot MeV})^{-1}$ above 1650 MeV and a constant $2 \cdot 10^{-5}(\mathrm{cm^2 \cdot s \cdot sr \cdot MeV})^{-1}$ below 1650 MeV provides a reasonable difference of 1.25% between reference count rates calculated for the Moscow and Apatity NMs.

The solar cosmic ray variations can be expressed by an integral

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

where $\delta J(E)_{\mathrm{sol}}$ is a spectrum of solar protons and $E_{\max}$ is their maximum energy. Hourly average uncorrected data from two integral channels of the GOES-7 proton detector were used to evaluate the spectrum of solar and shock-associated protons. 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 the interval of 84–500 MeV, one can estimate its power law index and normalizing constant from the observed ratio of channel count rates (Belov et al., 1995). If the observed enhancement is really caused by this population of particles, then by varying $E_{\max}$ for a given time moment it is possible to obtain the desired coincidence of 0.1% between the observed and expected values of solar CR variations. If the derived spectrum $\delta J(E)_{\mathrm{sol}}$ beginning from some energy E is less than $0.1 \cdot J_0(E)$, then it is assumed that the spectrum is too soft and cannot result in the observed variations, so $E_{\max} = E$. The NM response to the shock-associated particles can be estimated using the same technique. An estimate for the geomagnetic variations is

$$\delta N_{\mathrm{geo}} \approx \int_{E_c}^{E_c^0} g(E,x)J_0(E)dE\,. \tag{4}$$

Since E_c would likely be within 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 obtain a better accuracy of geomagnetic variations.

By removing the solar and geomagnetic CR variations from the total CR variations, a value of the precursory increase for mid- and high-latitude NMs can be estimated.

3 Results and discussion

3.1 Precursory increase

Figure 1 from top to bottom illustrates the step-by-step calculations of the Forbush precursory increase in Moscow. The power law index γ (second panel) was estimated from the ratio of integral proton fluxes within 84–200 MeV and 110–500 MeV energy bands (first panel) that were measured aboard GOES-7. The integral (3) was calculated within limits of E_c and $E_{\max}$ (third panel).

By varying the maximum energy of solar protons $E_{\max}$, a reasonable coincidence between the observed (total) CR variations and the calculated solar CR variations for the Moscow NM is achieved during the isotropic phase of the 19 October 1989 GLE (fourth panels). However, there is a visible discrepancy of about 2% from 05:00 UT until about 12:00 UT, i.e. the spectrum deduced from the GOES data appeared to be too soft to explain the observed variations. This discrepancy coincides in time with the precursory increase observed by low-latitude NMs and should be caused by the same variations of CR with very hard spectrum $\delta J(E)_{\text{int}}$. The precursory increase lasted from ∼05:00 UT until ∼12:00 UT, so galactic cosmic rays penetrated easily the first shock and were scattered effectively by the magnetic barrier behind the shock. This implies that the propagation mean free path of CR protons downstream of the barrier was ∼0.1 AU.

3.2 Shock-associated increase

Figure 2 shows the modulation parameter $B \cdot V$, where B is the total IMF magnetic field strength and V is the solar wind velocity; the GOES-7 proton data are in linear scale and the interplanetary variations are deduced for the Apatity and Moscow NMs. The $B \cdot V$ parameter plays a crucial role in theoretical models of Forbush decreases (Wibberenz et al., 1998) It is clear from Fig. 1 that CR variations estimated from the GOES data are greater than the variations observed in Moscow after 12:00 UT. This time represents a real onset of the Forbush decrease in Moscow (Fig. 2, fourth panel). The increase in shock-associated particles started at about the same time and coincided with the first maximum of the $B \cdot V$ parameter. Cosmic ray variations in Apatity show the similar behavior (Fig. 2, third panel).

The spectrum of shock-associated particles deduced from GOES data was very soft (Fig. 1, second panel). The maximum energy of these particles was less than 1 GeV and they resulted in the statistically significant enhancement in Moscow only due to changes in the geomagnetic cutoff (Fig. 1, third panel). Note that protons with approx. energy of the atmospheric cutoff were observed between 13:00–19:00 UT in the stratosphere above Moscow (Struminsky, 1992).

The shock wave on 20 October 1989 was one of the strongest in the 22nd solar cycle, considering its effects on cosmic rays and the magnetosphere, so the obtained value of 1 GeV may provide the upper energy limit of the shock acceleration at a distance of 1 AU in the heliosphere.

However, the shock-associated particles arrived well after SSC and looked like they were trapped between two magnetic barriers. These barriers correspond to maximums of the $B \cdot V$ parameter: $B_1 \cdot V_1 = 22.7$ nt · 631 km/s at 13:00 UT and $B_2 \cdot V_2 = 22.9$ nt · 785 km/s at 18:00 UT. A distance between the magnetic walls was ∼0.09 AU at the Earth's orbit and it should be greater near the Sun. Apparently, this is a radial dimension of the magnetic trap and a mean free path of particles inside the trap in this direction.

3.3 Acceleration versus trapping

The nature of the shock-associated particles on 20 October 1989 is not clear. The main question is, were these particles accelerated near the flare site and then injected into the trap or were they accelerated by the shock from thermal energies?

In the case of the classical shock acceleration, the spectrum of shock accelerated particles should become harder, if a shock wave is approaching the observer, but the opposite is true for 20 October 1989 (Fig. 1, second panel). However, it would not be so for a shock-like acceleration in a compressing trap.

Let us discuss possibility of particle acceleration between the converging magnetic barriers. An average relative increase of particle energy as a result of one acceleration act (scattering from front and rear barriers) would be

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

and a number of possible acceleration acts is

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

where $T \approx 24$ hours is a propagation time of the magnetic trap to Earth. The initial energy of the particles might increase by a factor of $\beta^k = 3.68$ inside the trap on its way to the Earth. The energy of protons should be at least of several hundred MeV in order to increase their spectrum up to 1 GeV near the Earth.

Therefore, the shock-associated protons should be accelerated primarily near the Sun, possibly along with the GLE protons, and then they should be injected into the trap. The proton spectrum in the trap was softer than in the GLE main phase, because the trap was not effective for energies of several hundred MeV. Note that this interplanetary structure effected simultaneously only 1–2% of galactic cosmic rays.

Lario and Decker (2002) reached a similar conclusion independently that the high-energy proton population observed around the shock passage is not a locally shock-accelerated population, but rather a population confined and channeled by a complex magnetic field structure.

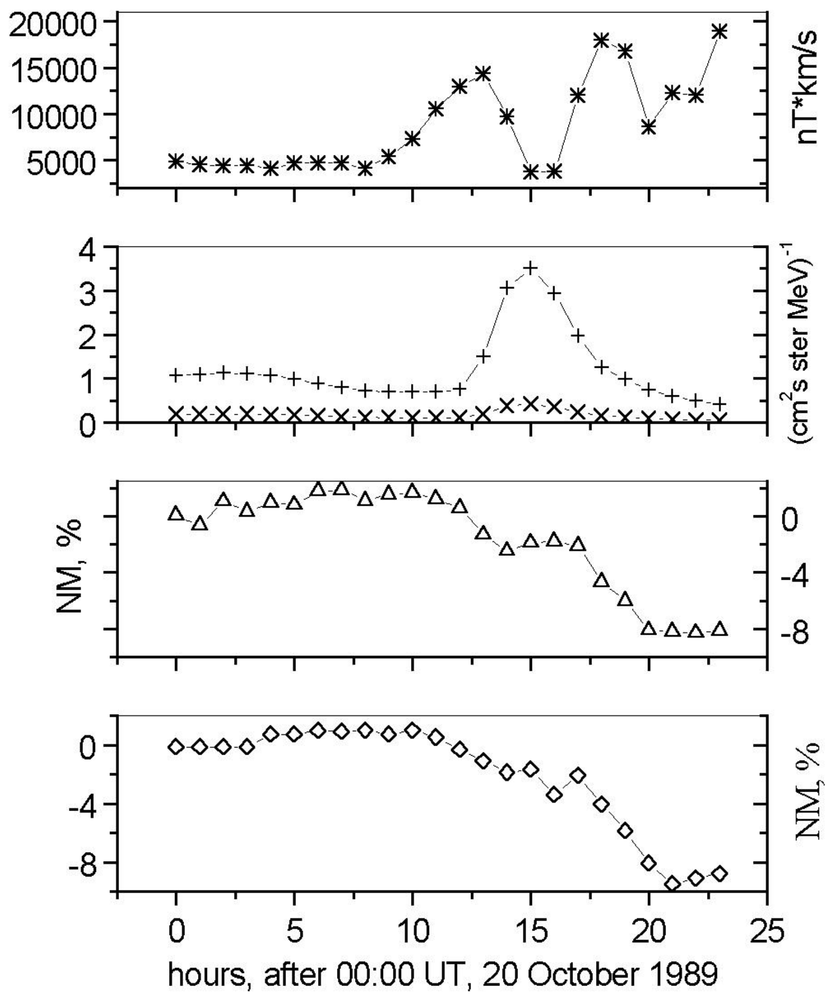

Fig. 2. The total IMP magnetic field strength (nT) multiplied by the solar wind velocity (km/s); proton flux within 84–200 and 110–500 MeV energy bands measured by the GOES-7 detector; variations of interplanetary origin estimated for the Apatity (open triangles) and Moscow (open diamonds) NMs.

4 Summary

The Forbush effect on 20 October 1989 was observed on the background of the 19 October 1989 GLE during the large geomagnetic storm. Effects of solar and geomagnetic variations were eliminated from total CR variations of the Apatity and Moscow NMs in order to estimate the Forbush precursory increase and the shock-associated enhancement on 20 October 1989. Different data sets of ground and space borne detectors were used in this procedure.

Solar cosmic ray variations were deduced from the GOES-7 proton data, assuming changes in the geomagnetic cutoff in Moscow. A reasonable agreement between observed and estimated solar CR variations was obtained during the GLE isotropic phase early in the morning of 20 October 1989. The estimated geomagnetic variations of galactic CR were less than 1.5%.

The Forbush pre-increase had a very hard spectrum with maximum energy more than 10 GeV. The shock-associated particles had a soft spectrum with maximum energy less than 1 GeV. They caused only a small increase in the Moscow NM count rate due to changes in the cutoff rigidity. The precursory increase and the shock-associated enhancements were clearly separated in time and, therefore, they should be attributed to different populations of CR.

The Forbush pre-increase was caused by a single reflection of galactic cosmic rays from the shock. The shock-associated particles were trapped between two magnetic walls. These particles were accelerated close to the Sun; their initial energy might increase by a factor of four only on the way to Earth.

Acknowledgements. 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, 99-02-16289 and 01-02-17580). The author is grateful to all researchers provided their data to the Space Physics Interactive Data Resource and acknowledges an anonymous referee for his/her useful comments and suggestions.

Topical Editor E. Antoucci thanks a referee for his help in evaluating this paper.

References

Bavassano, B. N., Lucci, N., Lepping, R. P., Signorini, C., Smith, E. J., and Villoresi, G.: Galactic Cosmic Ray Modulation and Interplanetary Medium Perturbations due to a Long-living Active Region during October 1989, J. Geophys. Res., 99, 4227, 1994.

Bazilevskaya, G., Stozhkov, Yu., and Struminsky, A.: The Influence of Interplanetary Shocks on Solar protons Measured in the Stratosphere, Adv. Space Science, 14, 10, 10 717–10 720, 1994.

Belov, A. and Struminsky, A.: Neutron Monitor Sensitivity to Primary Protons below 3 GV Derived from Data of Ground Level Events, ICRC 25th, 1, 201, Durban, South Africa, 1997.

Belov, A., Chertok, I., and Struminsky, A.: Time Evolution of Solar Proton Energetic Spectra at the Earth Orbit and Possibility of MultiStep Particle Acceleration, ICRC 24th, 4, 127, Rome, Italy, 1995.

Cane, H. V.: Coronal Mass Ejections and Forbush Decreases, Space Science Review, 93, 55–77, 2000.

Cane, H. V. and Richardson, I. G.: Cosmic Ray Decreases and Solar Wind Disturbances during Late October 1989, J. Geophys. Res., 100, 1755–1762, 1995.

Clem, J. M. and Dorman, L. I.: Neutron Monitor Response Functions, Space Science Review, 93, 335–359, 2000.

Cliver, E. W., Feynman, J., and Garret, H. B.: An estimate of the Maximum Speed of the Solar Wind, 1938–1989, J. Geophys. Res., 95, A10, 17 103–17 112, 1990.

Fluckiger, E. O., Smart, D. F., and Shea, M. A.: A procedure for estimating the changes in cosmic ray cutoff rigidities and asymptotic directions at low and middle latitudes during periods of enhanced geomagnetic activity, J. Geophys. Res., 91, 7925, 1986.

Kallenrode, M.-B.: A Statistical Study of the Spatial Evolution of Shock Acceleration Efficiency for 5 MeV Protons and Subsequent Particle Propagation, J. Geophys. Res., 102, A10, 22 335–22 345, 1997.

Klein, K.-L., Chupp, E. L., Trottet, G., Magun, A., Dunphy, P. P., Rieger, E., and Urpo, S.: Flare-associated Energetic Particles in the Corona and at 1 AU, Astron. Astrophys., 348, 271–285, 1999.

Lario, D. and Decker, R. B.: The energetic Storm Particle Event of October 20, 1989, Geophys. Res. Lett., 29, accepted, 2002.

Lim, T. L., Quenby, J. J., Reuss, M. K., Keppler, E., Kunow, H., Heber, B., and Forsyth, J. R.: Can Diffusive Shock Acceleration Work Fast Enough in Interplanetary Shocks? Evidence from the November 1992 Event, ICRC 24th, 4, 353–356, 1995.

Struminsky, A.: Investigation of Modulation Effects in Solar Cosmic Rays, Ph. D. theses (in Russian), Lebedev Physical Institute, Moscow, 1992.

Struminsky, A.: Forbush Decrease on 20–22 October 1989: Solar Protons, Interplanetary and Magnetospheric Variations, ICRC 27th, 9, 3558–3561, 2001.

Struminsky, A. and Lal, M.: Magnetospheric Currents and Variations of Cutoff Rigidities on October 20, 1989, ICRC 27th, 10, 4053–4056, 2001.

Wibberenz, G., Le Roux, J. A., Potgieter, M. S., and Bieber, J. W.: Transient Effects and Disturbed Conditions, Space Sci. Rev, 83, 309–348, 1998.