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Cosmic Rays during Forbush Effects in March 1989 and March 1991: Spectra of Variation, Anisotropy, and Variations of Geomagnetic Cutoff Rigidity

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Abstract—Two Forbush effects that occurred during geomagnetic storms in March 1989 and March 1991 are analyzed based on ground-based measurements of cosmic rays at a global network of stations via spectrographic global survey. The rigidity spectra and variation spectra are presented, as well as the pitch-angle anisotropy of cosmic rays at different phases of the development of Forbush effects and variations in the planetary system of geomagnetic cutoff rigidities. It is shown that, when the variation spectra are approximated by a power-law function of particle rigidity in the range of 10–50 GV, the spectrum index in the phase of maximum modulation is softer than in the decline and recovery phases of cosmic-ray intensity. The distance to the subsolar point and the radius of the ring current, as well as the contribution of the ring current to variations in the geomagnetic cutoff rigidity and the *Dst* index, are determined within an axisymmetric model of the Earth's limited magnetosphere that takes into account the magnetopause currents and ring current.

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1. INTRODUCTION

Variations in the secondary cosmic rays (CRs) detected by ground-based equipment are an integral result of various solar, heliospheric, magnetospheric, and atmospheric phenomena. An example of the influence of solar activity on CRs are Forbush effects, which are rapid decreases in the CR intensity observed on Earth (Forbush, 1937). Forbush effects provide direct information on disturbances in the interplanetary medium, since their parameters are closely related to phenomena in solar–terrestrial physics. They stand out from other cosmic ray variations in magnitude, frequency of occurrence, and diversity. The reasons for the diversity of Forbush effects are the influence of various solar sources and their variability, as well as the properties of the propagation of a disturbance in the interplanetary medium and its interaction with the heliospheric current sheet, etc. Thus, the variation in galactic cosmic rays contains information on the electromagnetic characteristics of interplanetary disturbances and the interplanetary magnetic field (IMF). In this regard, studies of the Forbush effects are relevant and practically important for CR astrophysics, the physics of solar–terrestrial relations, geophysics, and space-weather forecasting. The relevance of the problem is indicated by the steady flow of publications on the subject of Forbush effects (e.g., Belov et al., 2014; Belov et al., 2016; Livada et al., 2018; Melkumyan et al., 2019).

In this study, we calculated the spatial and energy characteristics of two Forbush effects observed in March 1989 and in March 1991 in order to obtain additional information for an understanding of the nature of these phenomena. The studied events were accompanied by geomagnetic storms (the largest in the 22nd solar cycle) that caused massive disruptions in the power supply system, as well as numerous communication disruptions and satellite malfunctions (Kappenman and Albertson, 1990; Smart et al., 1995). To solve this problem, heliospheric sources of geomagnetic disturbances based on satellite observations were considered (Section 3); the results are discussed in Section 4, and the summary is presented in Conclusions.

2. EXPERIMENTAL

Data from a global network of neutron monitor stations were used for the analysis. They were corrected for pressure and averaged over hourly intervals. The study of the event of March 1989 involved data from 43 neutron monitors; the modulation amplitudes were counted from the background level of March 2, 1989. The study of the event of March 1991 involved data from 46 neutron monitors, and the modulation amplitudes were measured from the background level of March 3, 1991 (http://center.stelab.nagoya-u.ac.jp/WDCCR).

The quiet period is chosen, because the electromagnetic environment in the interplanetary space and the geomagnetic environment were calm in these periods, as compared with periods of geomagnetic disturbances, and the spectrum of galactic cosmic rays was the least modulated. Data from the GOES-7 spacecraft (http://satdat.ngdc.noaa.gov./sem/goes/data/new_avg/) was used in the analysis of the events in March 1989 and March 1991 (protons in seven energy intervals of 0.8–4; 4–9; 9–15; 15–40; 40–80; 80–165, and 165–500 MeV).

The analysis was conducted with the spectrographic global survey (SGS) method (Dvornikov et al., 1983; Dvornikov and Sdobnov, 2002; Kravtsova and Sdobnov, 2014, 2016, 2017). Unlike the existing research methods for CR variations, SGS allows the use of the entire available complex of ground-based recording equipment for analysis (a global network of neutron monitors located at different levels in the Earth's atmosphere, as well as ground-based and underground meson telescopes, etc.). This circumstance makes it possible, along with the phases of the first and second harmonics of the pitch angle anisotropy, to determine the rigidity spectrum of the isotropic component and CR anisotropy, to obtain information on the IMF orientation from the phase of the second harmonic, and to determine variations in the planetary system of geomagnetic cutoff rigidities for each hour of observation during periods of geomagnetic field disturbances. The reliability of the information obtained via SGS with data from the global network of CR stations is confirmed based on its comparison with the observed parameters of the IMF and the Earth's magnetosphere. The geomagnetic field in March 1989 and March 1991 was strongly disturbed. Unfortunately, there are almost no spacecraft data on the IMF for that period. Hofer and Flückiger (1997) provide the IMF variations on March 24, 1991 according to the measurements at the Galileo spacecraft. The maximum IMF values at some points on March 24, 1991, reached ~25 nT, and the average solar wind (SW) speed reached ~1400 km/s (Le et al., 2003). Nevertheless, we can use our calculated values of the anisotropy parameters and the rigidity spectrum (Dvornikov et al., 2013) for the studied period to draw conclusions about variations in the IMF. Within the context of the model of the CR modulation by the regular electromagnetic fields of the heliosphere, strong pitch-angle anisotropy is a reflection of the structural features of large-scale fields in interplanetary space (e.g., magnetic traps) caused by inhomogeneity along the heliolongitude and nonstationarity of the SW outflow at the source, i.e., it is an indicator of dynamic processes in the heliosphere. Variations in the IMF intensity are accompanied by an increase in the amplitudes A_1 and A_2 (bidirectional) of the harmonics of the pitch-angle CR anisotropy. As the Earth enters and exits structures like coronal mass ejections (CMEs), an increase in the amplitude A_1 is observed, while an increase in the amplitude A_2 indicates the presence of a loop-like structure in the IMF (Dvornikov et al., 2013).

An expression obtained in the model of the CR modulation by regular electromagnetic fields of the heliosphere was used to calculate the CR spectra (Dvornikov et al., 2013) under the assumption that the CR intensity with a certain rigidity varies in accordance with the Liouville theorem. The assumption is true when the effects of particle scattering by magnetic inhomogeneities can be disregarded and when there are no solar CRs in the consideration energy range.

The main feature of a magnetic storm is a rapid increase in the ring current due to the injection of charged particles from the magnetotail. During a magnetic storm, the rapid increase of the ring current due to the injection of charged particles from the magnetotail is accompanied by a significant amplification of other magnetospheric current systems: tail currents and magnetopause currents, as well as longitudinal and ionospheric currents, which are not taken into account in our model. The relationship between the contributions of these current systems to the *Dst* index at different phases of the magnetic storm can characterize their relative dynamics during magnetospheric disturbances.

In this study, we evaluate magnetospheric effects with the simplest axisymmetric model of a limited magnetosphere; the radii of the ring current and magnetopause current reflect the total contributions of several current systems. Therefore, it is more correct to speak of the effective radii of current systems that contribute to the *Dst* index like ring current and magnetopause current.

Some parameters of the magnetospheric current systems (DCF and DR) were calculated from the results of the SGS calculations of the dependences of the variations in the geomagnetic cutoff rigidity on the geomagnetic cutoff rigidities from the global network of CR stations (ΔR_{ob}) and the geomagnetic cutoff rigidity variations on the geomagnetic cutoff rigidities in the axisymmetric model of the limited magnetosphere of the Earth (ΔR_{cal}) (Kichigin and Sdobnov, 2017). These parameters in this model are the radius of the ring current (DR) r_c; the radius of magnetopause currents (DCF) r_m; and the *Dst* index. The parameters of the current systems (r_c, r_m) are determined by the enumeration of these parameters and the values of the *Dst* index to minimize the function

$$\left(\sum_i [\Delta R_{\text{ob}}(R_i) - \Delta R_{\text{cal}}(R_i, r_c, r_m, Dst)]^2\right) = \min.$$

3. HELIOSPHERIC SOURCES OF GEOMAGNETIC DISTURBANCES

3.1. March 1989

On March 6, 1989, active region (AR) 5395 appeared on the east limb of the Sun (coordinates 35° N, 69° E); from March 6 to 19, it produced 11 X-class X-ray flares, 48 M-class X-ray flares, and ~10 coronal mass ejections (CMEs) of various strength (from weak to bright). Such colossal solar activity had many important consequences on the Earth and in the near-Earth space. Events that occurred on the Sun generated a giant magnetic storm on Earth, strong ionospheric disturbances, and a huge decrease in CR intensity (Forbush effect) (Allen et al., 1989; Venkatesan et al., 1990; Fujii et al., 1992; Nagatsuma et al., 2015).

The geomagnetic storm that developed on March 13–14, 1989 was the most extreme disturbance since 1957. It was caused by a CME from the X4.5/3B solar flare of March 10 (Allen et al., 1989). This CME was not exceptional in terms of its speed (~770 km/s) (Feynman and Hundhausen, 1994). However, Feynman and Hundhausen (1994) noted its high brightness, which manifested itself in strong dynamic pressure on the Earth's magnetosphere. The geomagnetic storm reached its maximum intensity on March 13, when the planetary *Ap* index increased to 246, and the geomagnetic activity *Dst* index (between 0100 and 0200 UTC on March 14) reached –589 nT (Venkatesan et al., 1990; Allen et al., 1989). The likelihood of an event of such a scale is once in 60 years (Tsubouchi and Omura, 2007).

This event is well known for its practical implications. The strong, geomagnetically induced current that flowed through power lines caused a power system collapse in North America (Kappenman and Albertson, 1990; Bolduc, 2002). As a result, six million Quebec residents were left without electricity for more than 9 h. In addition, a low-latitude aurora was visible in the southern United States on the night of March 13 and early in the morning of March 14.

In Irkutsk (geomagnetic cutoff rigidity $Rc = 3.66$ GV), the count rate of the neutron monitor decreased by ~–12% relative to the quiet period of March 2, 1989.

3.2. March 1991

Intense solar activity in three ARs (6538, 6545, 6555) from March 22 to 23, 1991 led to strong disturbances in the near-Earth space and the Earth's magnetosphere. On March 22 at 2243 UT, there was a 3B/X9.4 flare (coordinates 26° S, 28° E) that produced a shock wave with type-II radio emission. The flare was accompanied by a fast CME; its speed reached 1400 km/s (Le et al., 2003). The shock wave reached the Earth at 0342 UT on March 24, 1991, and caused a sudden storm commencement (SSC). The magnetopause shifted to 6.6 Earth radii (Smart et al., 1995). The *Kp* index increased to 9, and the *Dst* index of geomagnetic activity reached –298 nT. Auroras were observed in Australia. In addition, this geomagnetic storm had technological consequences (Smart et al., 1995), such as damage to the solar panels of the GOES-6 and 7 spacecraft and power outages in the United States, Canada, and central Australia. At the same time, the onset of a giant Forbush effect was detected (Hofer and Flückiger, 1997, 2000; Ahluwalia et al., 2009).

The maximum amplitude of the decrease in the count rate of the neutron monitor in Irkutsk was ~–23%.

4. RESULTS AND DISCUSSION

4.1. Spectra of CR Variations and Anisotropy

Figure 1 shows the amplitudes of variations in the CR neutron component ($\Delta I/I$) at Irkutsk station (R_c = 3.66 GV) during the Forbush effects in March 1989 and March 1991, the amplitudes of CR variations with rigidity of 4 and 10 GV at the magnetospheric boundary ($\Delta J/J$), and the amplitudes of the first (A_1) and second (A_2) harmonics of the pitch-angle anisotropy for particles with rigidity of 4 GV, as well as variations in the geomagnetic cutoff rigidity (ΔR) in Irkutsk combined with the *Dst* index.

Although the magnetic storm in March 1991 (*Dst* index ~–300 nT) was less intense than that in March 1989 (*Dst* index ~–600 nT), the amplitude of the effect in the count rate of the neutron monitor in Irkutsk in March 1989 relative to its onset (~–12%) was lower than in March 1991 (~–18%), while the amplitude of the effect for particles with rigidity of 4 and 10 GV at the magnetospheric boundary relative to the onset of the event in March 1989 was greater than for March 1991. The maximum increase in the amplitude of the first harmonic of the pitch-angle anisotropy in the March 1989 event was ~30% and ~40% on March 13 and 15, respectively. In March 1991, the maximum increase in the amplitude of the first harmonic of the pitch-angle anisotropy from ~30% to ~50% occurred on March 25, 26, and 27. The amplitudes of the second harmonic of the pitch-angle anisotropy during the events of March 1989 and March 1991 reached ~8–10%, but the amplitude of the second harmonic of the pitch-angle anisotropy increased to ~30–40% from 1400 to 1900 UT on March 24, 1991.

Variations in the geomagnetic cutoff rigidity in Irkutsk in March 1989 and in March 1991 reached ~–1.3 and ~1.0 GV, respectively. The correlation coefficient between the variations in the geomagnetic cutoff rigidity in Irkutsk and the *Dst* index was ~0.8 for the period from March 11 to March 22, 1989, and 0.75 for the period from March 20 to 29, 1991.

Figure 2 shows the rigidity spectra and the spectra of variations of the primary CRs at individual points in different development phases of the studied events. It can be seen that, in all the presented instants of the

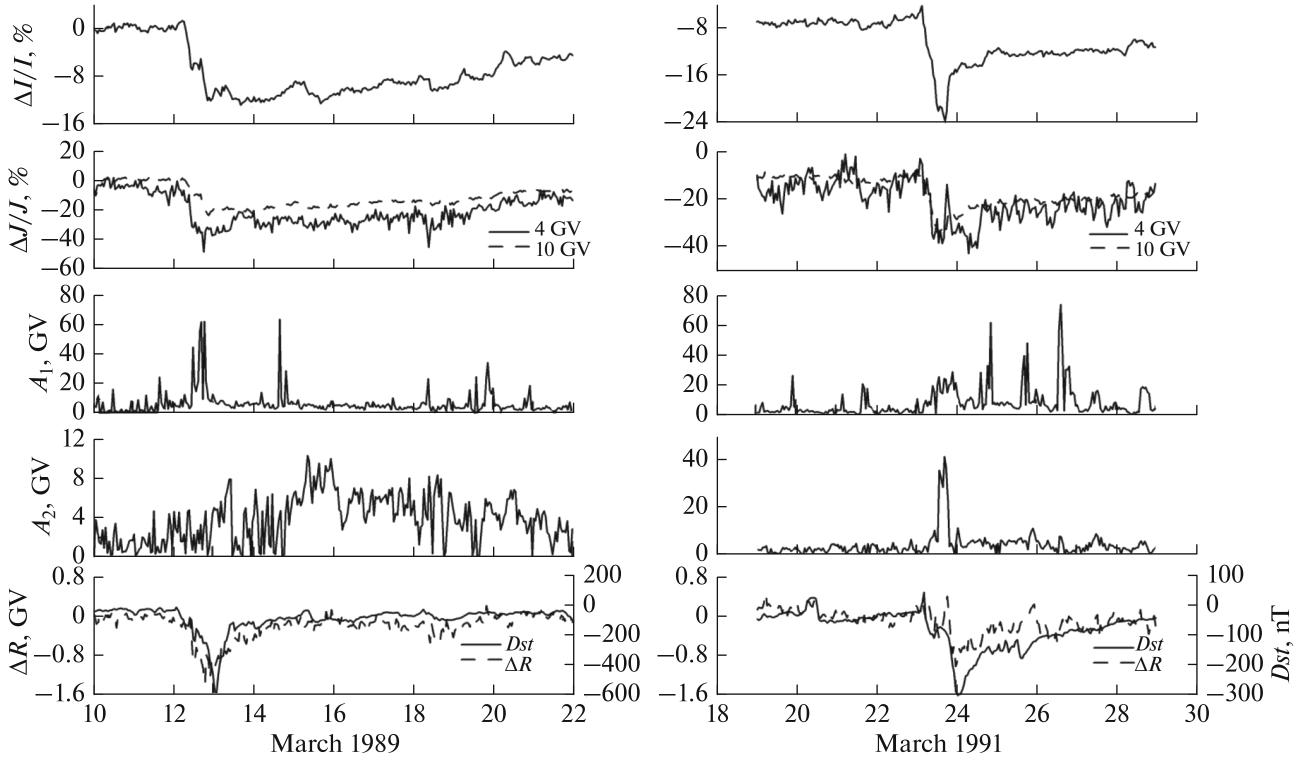

Fig. 1. For the period of March 10–22, 1989 (left panel) and March 18–30, 1991 (right panel): (a) variations of the CR neutron component at Irkutsk station; (b) variations in the isotropic component of the intensity of primary CRs with a rigidity of 4 GV (solid curve) and 10 GV (dashed curve); (c, d) amplitudes of the first A_1 and second A_2 harmonics of the pitch-angle distribution of CRs with a rigidity of 4 GV; (e) the time course of the variations in the geomagnetic cutoff rigidity in Irkutsk (R_c = 3.66 GV) (dashed curve) together with the *Dst* index (solid curve).

Forbush effects, the proton intensity in the Earth's orbit in the rigidity spectra below ~1 GV is higher than the background level, while the proton intensity at higher energies is lower than the background level, i.e., Forbush effects are observed in the sensitivity range of neutron monitors. The spectra of CR variations do not follow the power law in a wide range of rigidities. Only in a rigidity range above ~10 GV are these spectra close to a power law.

When representing the spectra of variations in primary CRs, we calculated the exponents γ with a power function in the rigidity range above ~10 GV. Table 1 shows the average value of the exponent γ for the studied events when the rigidity spectra of variations are approximated by a power-law function of particle rigidity in the range of 10–50 GV. It can be seen that, on average, the spectra of CR variations in the rigidity range from 10 to 50 GV in the event of March 1989 are softer than those for the Forbush effect in March 1991. For both events, the spectra of CR variations, as in other cases (Kravtsova and Sdobnov, 2014, 2016, 2017), at the points of maximum modulation are softer than at the phases of decline and recovery of the CR intensity.

Figure 3 shows the relative variations in the CR intensity for particles with a rigidity of 4 GV in the geocentric solar ecliptic coordinate system at different phases of the development of the studied Forbush effects.

Table 1. Average value of the exponent γ for the studied events when the rigidity spectra of variations are approximated with a power-law function of particle rigidity in the range from 10 to 50 GV.

Event date	Developmental phase of the Forbush effect		
	decline	maximum modulation	recovery
March 1989	~ –0.9	~ –1.0	~ –0.9
March 1991	~ –0.8	~ –0.9	~ –0.8

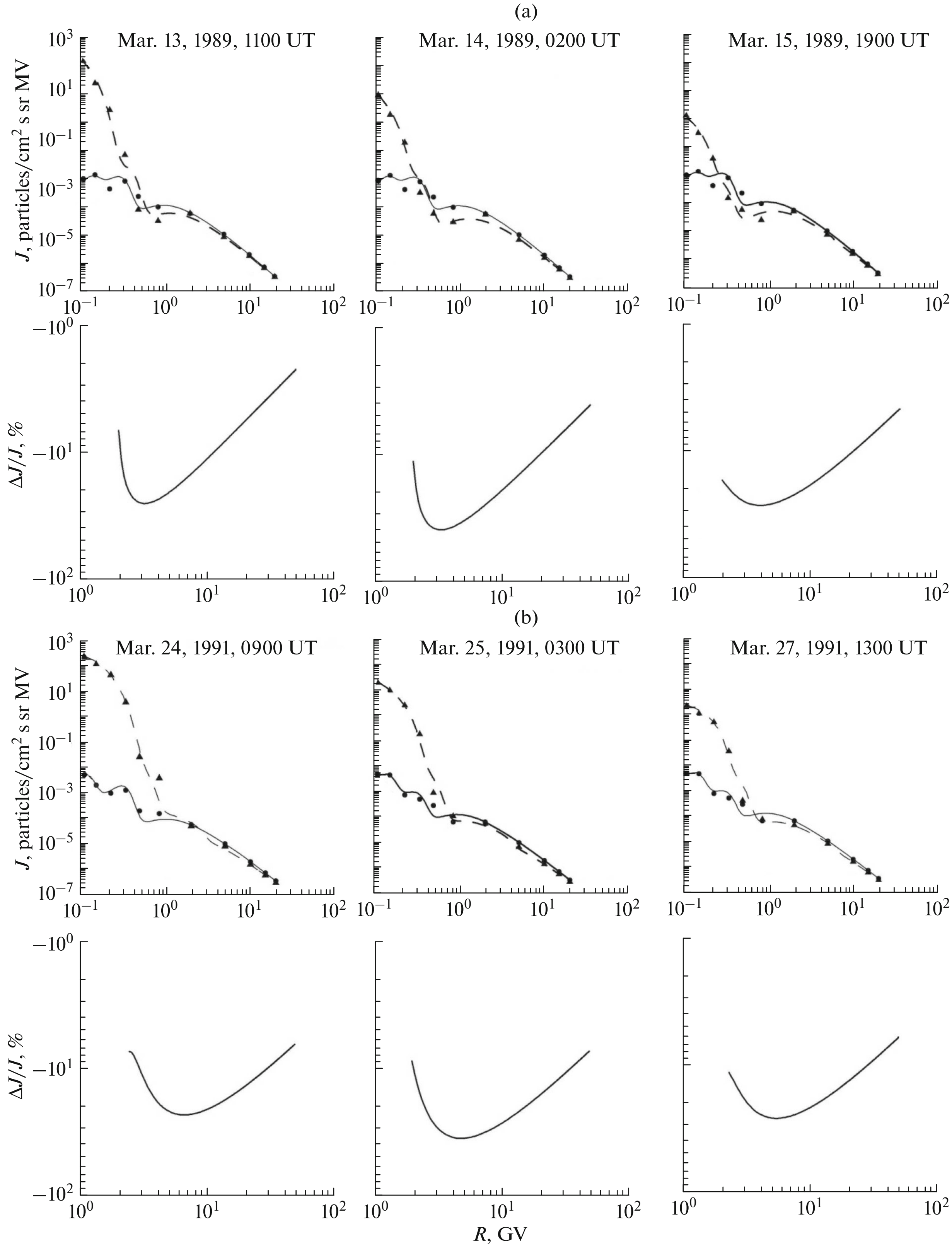

Fig. 2. Rigidity spectra and spectra of primary CR variations at different phases of development of the Forbush effects: (a) March 1989; (b) March 1991. The dashed curve is the calculated model spectrum at the indicated time point; the solid curve is the calculated background spectrum; the symbols are the observational data.

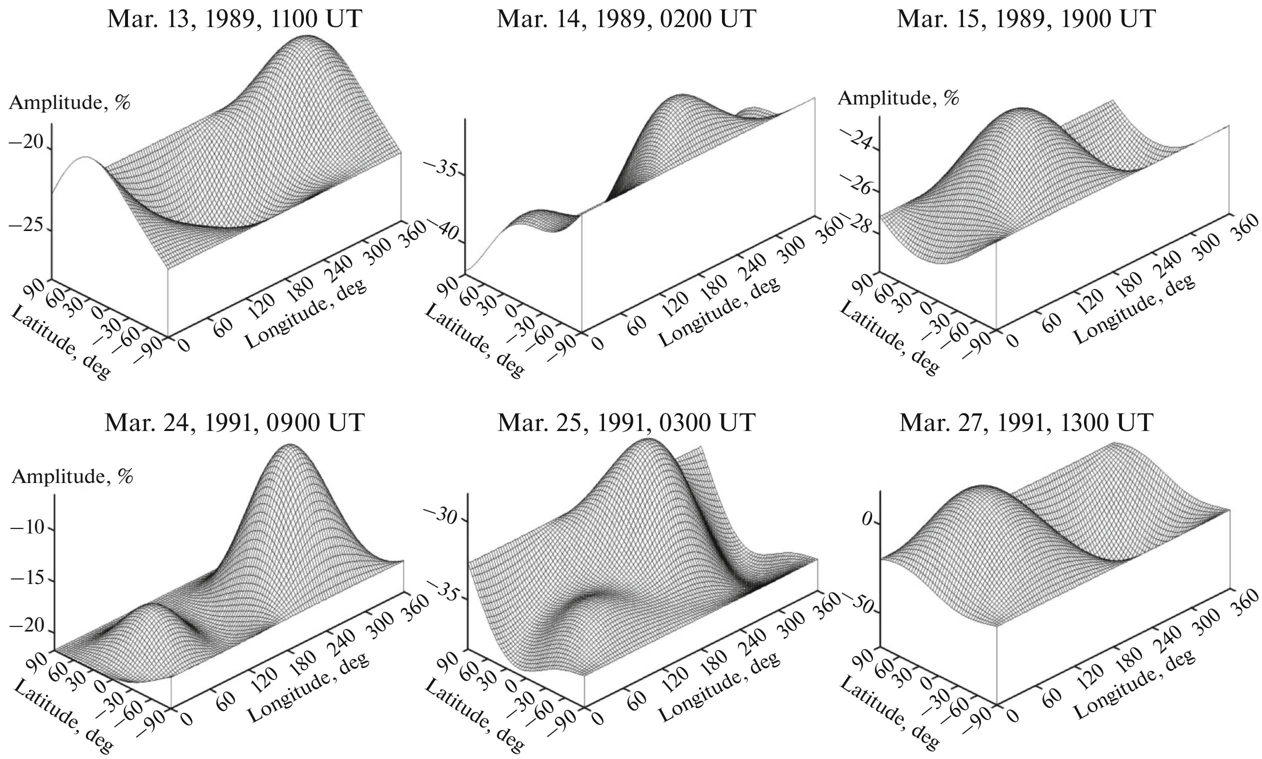

Fig. 3. Relative variations in the CR intensity for particles with a rigidity of 4 GV in the geocentric solar ecliptic coordinate system at different phases of the development of the Forbush effects. The abscissa represents the longitudinal angle ψ; the ordinate represents the latitudinal angle λ.

The abscissa represents the longitudinal angle ψ, and the ordinate represents the latitudinal angle λ. At one point of the decline phase at 1100 UT on March 13, 1989, one can see the first harmonic of the pitch-angle distribution with an increased particle flux from the direction with the geocentric solar ecliptic coordinates ψ = ~309° and λ = ~42°. At the same developmental stage, at 0900 UT on March 24, 1991, there was bidirectional anisotropy with an increased particle flux from the directions ψ = ~75°, λ = ~15° and ψ = ~255°, λ = ~–15°. At one point of the maximum modulation phase at 0200 UT on March 14, 1989, there is the second harmonic of the pitch-angle distribution with an increased particle flux from directions with the geocentric solar ecliptic coordinates ψ = ~20°, λ = ~25° and ψ = ~200°, λ = ~–25°; at 0300 UT on March 25, 1991, they occur from the directions ψ = ~51°, λ = ~–34° and ψ = ~230°, λ = ~ –34°. In the decline phase of the Forbush effect at 1900 UT on March 15, 1989, the first harmonic of the pitch-angle distribution with an increased particle flux from the direction with coordinates ψ = ~117°, λ = ~–12° is visible; at 1400 UT on March 27, 1991, it is visible from the direction ψ = ~22°, λ = ~56°. The calculations showed a large amplitude of bidirectional pitch-angle anisotropy from 1400 to 2000 UT on March 24, 1991, which is consistent with the results of Le et al. (2003). Hofer and Flückiger (2000) suggested that solar activity at 2245 UT on March 22, 1991, led to a CME, followed by a magnetic cloud with a spatial extent of approximately 0.4 AU. In their opinion, the Earth during this period was in a strong loop-shaped structure of the IMF.

Planetary variations in the geomagnetic cutoff rigidity were calculated based on the CR intensity variations from the global network of stations during the periods of magnetic storms coinciding with the Forbush effects in March 1989 and March 1991. Based on the obtained planetary variations in the geomagnetic cutoff rigidity within the axisymmetric model of the limited magnetosphere (Kichigin and Sdobnov, 2017) that takes into account the magnetopause currents and the ring current, we calculated the distance to the subsolar point, the radius of the ring current, ring-current strength (I_{DR}), and magnetopause-current strength (I_{DCF}), as well as the ratio between the contributions from these currents to the *Dst* index at different phases of the magnetic storm.

4.2. Magnetospheric-Current Systems at Different Phases of Storm Development

Figure 4 shows the geomagnetic cutoff rigidity variations at separate points of different phases of geomagnetic storms in March 1989 and in March 1991 as a

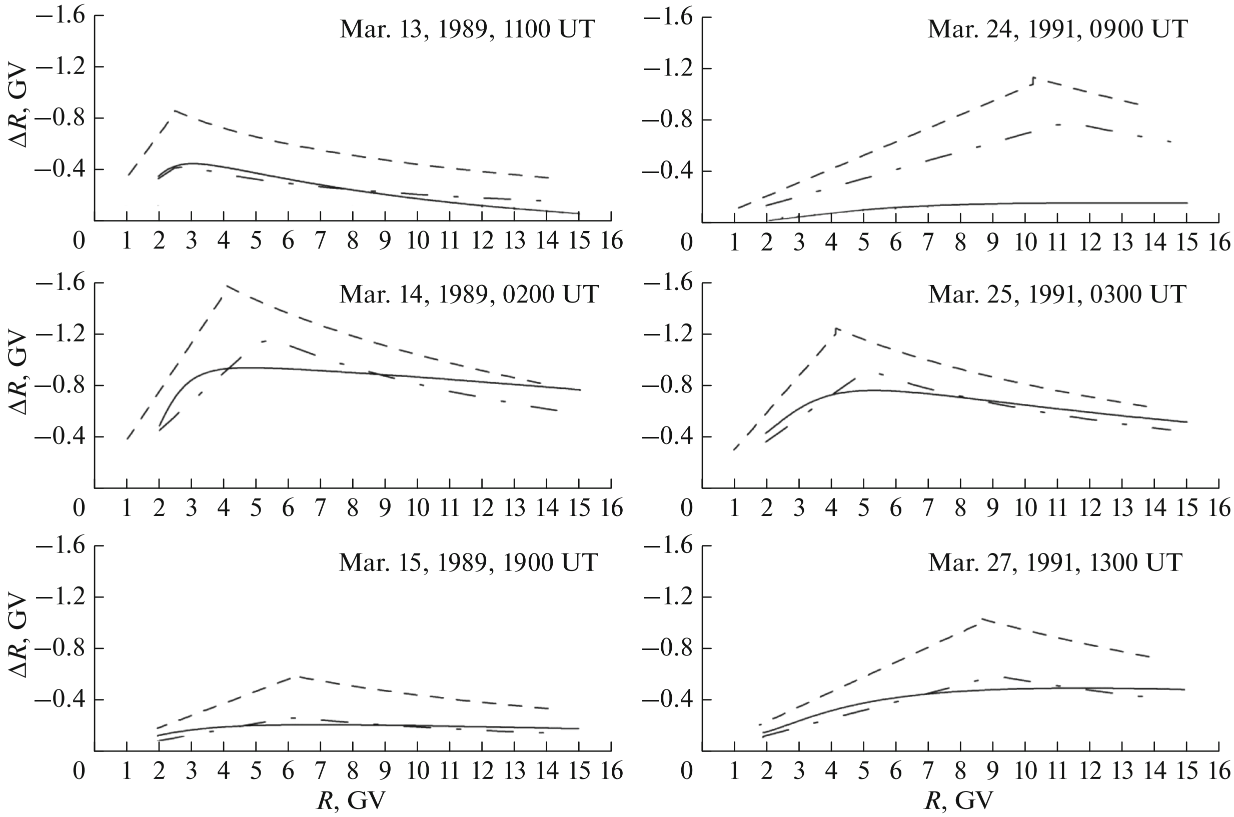

Fig. 4. Variations in geomagnetic cutoff rigidity as a function of geomagnetic cutoff rigidities at different phases of geomagnetic storms in March 1989 and in March 1991. The solid line shows the results obtained via SGS from the data of the global network of CR stations; the dash-dotted line shows the calculation in the axisymmetric model of the limited magnetosphere with the ring current. The dashed line is the contribution to the geomagnetic cutoff rigidity variations from the ring current calculated in the axisymmetric model of the limited magnetosphere.

function of the geomagnetic cutoff rigidities. It can be seen that, at the phases of the most intensive development of the magnetic storm and at the phases of its decline, the results of the calculations of the geomagnetic cutoff rigidity variations based on the observations of CR intensity at the global network of stations are described well by the axisymmetric model of the limited magnetosphere (Kichigin and Sdobnov, 2017), which includes only the ring current and the magnetopause currents.

Table 2 shows the observed (Dst_{obs}) and calculated (Dst_{calc}) values of the *Dst* index at different phases of magnetic-storm development, as well as the contribution of the ring current (Dst_{DR}) and magnetopause currents (Dst_{DCF}) to the total value of the *Dst* index and the strength of these current systems. The calculated parameters of the ring current and magnetopause current reflect the total contributions of several current systems. Therefore, it is more correct to speak of the effective radii of current systems that contribute to the *Dst* index, such as the ring current and magnetopause current.

Table 3 shows the mean ring current radii (r_c) in units of the Earth's radius and the mean distance to the subsolar point (r_m) in the axisymmetric model of the limited magnetosphere for different phases of geomagnetic-storm development. The minimum ring current radii are observed in the main phase of the geomagnetic storm, followed by an increase in the recovery phase of the geomagnetic disturbance. Since the axisymmetric model of the limited magnetosphere used in this study does not take into account the contribution of many current systems and the calculated values of the *Dst* index at some moments are close to the observed values, we can assume that the main contribution to their intensity in these periods is made by the symmetrical component DR and DCF of the currents.

5. CONCLUSIONS

Thus, the analysis has shown the following.

The spectra of CR variations during the Forbush effects in March 1989 and March 1991 do not follow the power law in a wide range of rigidities; these spectra are close to power law in rigidity only above ~10 GV.

Table 2. Contribution of the DR and DCF currents to the development of magnetic storms in March 1989 and March 1991

Date/Time	Dst_{obs}, nT	Dst_{calc}, nT	Dst_{DR}, nT	Dst_{DCF}, nT	$I_{DR} \times 10^6$ A	$I_{DCF} \times 10^6$ A
Mar. 13, 1989, 1100 UT	–101	–104	–226	122	13.9	3.7
Mar. 14, 1989, 0200 UT	–589	–400	–558	158	18.3	3.4
Mar. 15, 1989, 1900 UT	–99	–96	–285	129	13.6	1.4
Mar. 24, 1991, 1300 UT	–63	–432	–663	181	20.1	2.4
Mar. 25, 1991, 0300 UT	–294	–302	–425	123	15.1	2.5
Mar. 27, 1991, 1400 UT	–84	–110	–229	114	13.3	3.6

Table 3. Contribution of the DR and DCF currents to the development of magnetic storms in March 1989 and March 1991

Geomagnetic storm	Initial phase		Main phase		Recovery phase	
	r_c	r_m	r_c	r_m	r_c	r_m
March 1989	~4.5–5.0	~8.0	~3.5	~7.5	~4.0	~9.0
March 1991	~5.0–5.3	~7.0–7.2	~3.5	~7.5–8.0	~4.7	~9.0

When the variation spectra during the Forbush effects in March 1989 and March 1991 are approximated with a power-law function of particle rigidity in the range of 10–50 GV in the phase of maximum modulation, the spectrum exponent is higher than that in the decline and recovery phases of the CR intensity.

During the period of increased amplitude of the bidirectional pitch-angle CR anisotropy in the events of March 1989 and 1991, the Earth was in a loop-like structure of the IMF.

It was shown that, based on ground-based CR measurements at the global network of stations, it is possible to quantify the parameters of certain current systems in the magnetosphere during periods of magnetic storms.

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REFERENCES

Ahluwalia, H.S., Ygbuhay, R.C., and Duldig, M.L., Two intense Forbush decreases of solar activity cycle 22, *Adv. Space Res.*, 2009, vol. 44, pp. 58–63. https://doi.org/10.1016/j.asr.2009.04.004

Allen, J., Frank, L., Reiff, P., and Sauer, H., Effects of the march1989 solar activity, *EOS, Trans. Am. Geophys. Union*, 1989, vol. 70, no. 46, pp. 1479–1488. https://doi.org/10.1029/89EO00409

Belov, A., Abunin, A., Abunina, M., Eroshenko, E., Oleneva, V., Yanke, V., Papaioannou, A., Mavromichalaki, H., Gopalswamy, N., and Yashiro, S., Coronal mass ejections and non-recurrent Forbush decreases, *Sol. Phys.*, 2014, vol. 289, no. 10, pp. 3949–3960. https://doi.org/10.1007/s11207-014-0534-6

Belov, A.V., Eroshenko, E.A., Abunina, M.A., Abunin, A.A., Oleneva, V.A., and Yanke, V.G., Behavior of the cosmic ray density during the initial phase of the Forbush effect, *Geomagn. Aeron. (Engl. Transl.)*, 2016, vol. 56, no. 6, pp. 645–651. https://doi.org/10.7868/S0016794016060055

Bolduc, L., GIC observations and studies in the Hydro-Quebec power system, *J. Atmos. Sol.-Terr. Phys.*, 2002, vol. 64, no. 16, pp. 1793–1802. https://doi.org/10.1016/S1364-6826(02)00128-1

Dvornikov, V.M., Sergeev, A.V., and Sdobnov, V.E., Analysis of cosmic ray pitch-angle anisotropy during the June 1972 Forbush effect by method of spectrographic global survey, in *Proc. 18th ICRC*, Bangalore, 1983, vol. 3, pp. 249–252.

Dvornikov, V.M. and Sdobnov, V.E., Variations in the rigidity spectrum and anisotropy of cosmic rays at the period of Forbush effect on 12–15 July, *Int. J. Geomagn. Aeron.*, 2002, vol. 3, no. 3, pp. 217–226.

Dvornikov, V.M., Kravtsova, M.V., and Sdobnov, V.E., Diagnostics of the electromagnetic characteristics of the interplanetary medium based on cosmic ray effects, *Geomagn. Aeron. (Engl. Transl.)*, 2013, vol. 53, no. 4, pp. 430–440.
https://doi.org/10.7868/S001679401304007X

Feynman, J. and Hundhausen, A.J., Coronal mass ejections and major solar flares: The great active center of March 1989, *J. Geophys. Res.*, 1994, vol. 99, no. A5, pp. 8451–8464.

Forbush, S.E., On the effects in the cosmic-ray intensity observed during the recent magnetic storm, *Phys. Rev.*, 1937, vol. 51, pp. 1108–1109.

Fujii, R., Fukunishi, H., Kokubun, S., Sugiura, M., Tohyama, F., Hayakawa, H., Tsuruda, K., and Okada, T., Field-aligned current signatures during the March 13–14, 1989, great magnetic storm, *J. Geophys. Res.*, 1992, vol. 97, no. A7, pp. 10703–10715.
https://doi.org/10.1029/92JA00171

Hofer, M.Y. and Flückiger, E.O., Cosmic ray modulation during the 24 March 1991 Forbush decreases, in *Proc. 25th ICRC*, Durban, South Africa, 1997, vol. 1, pp. 401–404.

Hofer, M.Y. and Flückiger, E.O., Cosmic ray spectral variations and anisotropy near Earth during the March 24, 1991, Forbush decrease, *J. Geophys. Res.*, 2000, vol. 105, no. A10, pp. 23085–23097.

http://center.stelab.nagoya-u.ac.jp/WDCCR.

http://satdat.ngdc.noaa.gov./sem/goes/data/new_avg/.

Kappenman, J.G. and Albertson, V.D., Bracing for the geomagnetic storms, *IEEE Spectrum*, 1990, vol. 27, no. 33, pp. 27–33.

Kichigin, G.N. and Sdobnov, V.E., Geomagnetic cutoff rigidities of cosmic rays in a model of the bounded magnetosphere with the ring current, *Geomagn. Aeron. (Engl. Transl.)*, 2017, vol. 57, no. 2, pp. 132–136.
https://doi.org/10.7868/S0016794017020043

Kravtsova, M.V. and Sdobnov, V.E., Analysis of Forbush decreases during strong geomagnetic disturbances in March–April 2001, *Astron. Lett.*, 2014, vol. 40, no. 8, pp. 519–525.
https://doi.org/10.7868/S0320010814070043

Kravtsova, M.V. and Sdobnov, V.E., Cosmic rays during great geomagnetic storms in cycle 23 of solar activity, *Geomagn. Aeron. (Engl. Transl.)*, 2016, vol. 56, no. 2, pp. 143–150.
https://doi.org/10.7868/S0016794016020103

Kravtsova, M.V. and Sdobnov, V.E., Analyzing the June 2015 Forbush effect by the spectrographic global survey, *Bull. Russ. Acad. Sci.: Phys.*, 2017, vol. 81, no. 2, pp. 177–179.
https://doi.org/10.7868/S0367676517020259

Le, G.M., Ye, Z.H., Gong, J.H., Tan, Y.H., Lu, H., and Tang, Y.Q., Time determination of March 1991's CME hitting magnetosphere, in *Proc. 28th ICRC*, Tsukuba, Japan, 2003, pp. 3601–3604.

Livada, M., Mavromichalaki, H., and Plainaki, C., Galactic cosmic ray spectral index: The case of Forbush decreases of March 2012, *Astrophys. Space Sci.*, 2018, vol. 363, no. 8, p. 9.
https://doi.org/10.1007/s10509-017-3230-9

Melkumyan, A.A., Belov, A.V., Abunina, M.A., Abunin, A.A., Eroshenko, E.A., Oleneva, V.A., and Yanke, V.G., Recurrent and sporadic Forbush decreases during solar cycles 23–24, *J. Sol.–Terr. Phys.*, 2019, vol. 5, no. 1, pp. 28–34.
https://doi.org/10.12737/szf-51201904

Nagatsuma, T., Kataoka, R., and Kunitake, M., Estimating the solar wind conditions during anextreme geomagnetic storm: A case study of the event that occurred on March 13–14, 1989, *Earth Planets Space*, 2015, vol. 67, id 78.
https://doi.org/10.1186/s40623-015-0249-4

Smart, D.F., Shea, M.A., Fluckiger, E.O., and Sanahuja, B., Solar, interplanetary, and geomagnetic phenomena in March 1991 and their association with spacecraft and terrestrial problems, *Proc. Suppl. Nucl. Phys. B*, 1995, vol. 39A, pp. 26–34.
https://doi.org/10.1016/0920-5632(95)00004-S

Tsubouchi, K. and Omura, Y., Long-term occurrence probabilities of intense geomagnetic storm events, *Space Weather*, 2007, S12003.
https://doi.org/10.1029/2007SW000329

Venkatesan, D., Decker, R.B., Krimigis, S.M., Mathews, T., and Sarris, E.T., The great Forbush decrease of March 1989 and interplanetary energetic particle environment, in *Proc. 21th ICRC*, Adelaide, Australia, 1990, pp. 247–250.

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