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Effects of the April 1994 Forbush events on the fluxes of the energetic charged particles measured on board CORONAS-I: their connection with conditions in the interplanetary medium

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Abstract

The SONG instrument on board CORONAS-I satellite (fluxes of protons $E_p > 70$ MeV and electrons $E_e > 55$ MeV) observed the effects of the Forbush effects caused by interplanetary magnetic field sector boundary crossing and coronal mass ejection in April 1994. The latitudinal dependence of these effects is analyzed and compared with data from ground-based neutron monitors at different latitudes. It was found that while measurements by SONG instrument over the polar caps were in good agreement with the data of the neutron monitor at polar latitudes, at the middle latitudes during the D_{st} decreases, the cut-off rigidity variations were probably so strong that instead of the usual short-time decrease the SONG instrument detected a significant enhancement of particle fluxes. The influence of interplanetary medium conditions on the cosmic ray flux is analyzed and discussed. © 2002 Published by Elsevier Science Ltd.

Keywords: Galactic cosmic ray variations; Geomagnetic variations; Interplanetary perturbations

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1. Introduction

It is known that cosmic ray variations are caused by the changes of conditions in the interplanetary medium. Short-term cosmic ray variations (shortly named Forbush effects) are usually connected with sharp disturbances in the Earth's magnetosphere caused by coronal mass ejection (CME) connected with solar events and by interplanetary magnetic field (IMF) sector boundary crossing. Cosmic ray variations including even the short-term decreases are traditionally investigated by ground neutron monitors (NM) and by detectors on board near-Earth satellites detecting primary galactic cosmic rays (GCR) (e.g., Lockwood et al., 1991; Cane et al., 1994, 1995; Belov and Ivanov, 1997). These methods have their own difficulties. Since each neutron monitor has its individual acceptance cone and during each time of observation corresponds to a particular direction range from which the cosmic rays arrive at the Earth, investigation of Forbush effects and their spectra requires one to use the worldwide network of NMs situated on different longitudes and latitudes. Satellite particle measurements also have their own limitations. They do not permit to study Forbush effects in a broad interval of energies, due to the requirements on geometrical factors. The detector with sufficient geometric factor for cosmic ray detection on board a low-altitude satellite used as moving monitor of cosmic rays permits to observe Forbush effects at different latitudes and to study Forbush effect characteristics in dependence on cut-off rigidity with the same detector. Advantages of the method of GCR variations investigations in comparison with the ground NM were discussed in our earlier paper (Bogomolov et al., 1995). Preliminary results of Forbush effects measurements by SONG instrument during April 17, 1994 were published in Kuznetsov et al. (1999). In this paper, we analyze the observations of Forbush events during

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April 17 and April 3, 1994 at different latitudes by SONG instrument on board CORONAS-I satellite and compare them with NM data observed at several stations.

2. Experiment

The "CORONAS-I" satellite was launched on March 4, 1994 into a circular orbit with altitude 500 km and 83° inclination. "CORONAS-I" was oriented towards the Sun and was equipped with a set of instruments for studies of solar flares and corresponding solar cosmic ray (SCR) phenomena (Kuznetsov et al., 1995). GCR variations have been studied with the help of data, obtained by the SONG instrument. It is based on CsI(Tl) crystal (ø 20 and 10 cm thickness). The SONG instrument in the experiment on board "CORONAS-I" satellite was intended to detect gamma-rays and neutrons produced in solar flares. Energetic particle fluxes (with energy releases $E > 50$ MeV) were also detected by the SONG instrument. Such energy releases can be caused by protons ($E_p > 70$ MeV) and electrons ($E_e > 55$ MeV), (the geometric factor of SONG ≈2000 cm^2 sr). The SONG instrument was oriented along sunward direction.

In Fig. 1, the map of intensity of proton ($E_p > 70$ MeV) and electron ($E_e > 55$ MeV) flux detected by SONG instrument during March–June, 1994 (in geographical coordinates) is presented. The count rates of the SONG instrument were typically ≈600 particle/s in polar caps and ≈400 particle/s at the middle latitudes. The decrease of the particle flux as observed in the South Atlantic Anomaly Region is due to saturation effects of SONG the instrument used in this region.

The analysis of geomagnetic indices and interplanetary medium parameters during April 1994 obtained via Internet from NSSDC OMNIWeb (http://nssdc.gsfc.nasa.gov/omniweb/ow.html) indicated two interesting intervals, when significant disturbances in the Earth's magnetosphere were observed: the strong magnetic storm of April 17 ($D_{st} \approx -200$ nT), and the weaker one ($D_{st} \approx -100$–120 nT) beginning on April 2–3. Unfortunately, we have no continued solar wind parameters data for the total time interval from April 1 to 20 (more exactly, we have no solar wind data during April 2–4 and 15–19). However, based on our analysis of the time dependence of the solar wind velocity for a period of several months, we can say that the April 2–3 storm was associated with the magnetosphere passage across the boundary of a high-velocity solar wind stream. During the time interval April 6–14 solar wind data confirm that the Earth was then within a high-velocity solar wind stream. Considering the situation on the Sun (see for example, Veselovsky et al., 1997 and references therein) and the recurrent time dependence of the solar wind velocity, we assume that the high-velocity stream was finished on April 16. Later on the day of April 16, however, magnetic disturbances began, which developed into a strong geomagnetic storm. The storm was assumed to be induced by the CME generated on April 14 and associated with the SEP of April 14 (e.g., Veselovsky et al., 1997). On April 19, when the solar wind velocity data were obtained again, its velocity was below 700 km/s, and dropped to 400 km/s on April 23.

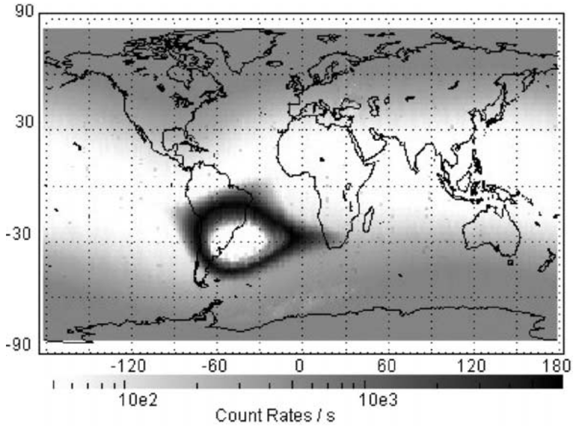

Fig. 1. Proton ($E_p > 70$ MeV) and electron ($E_e > 55$ MeV) flux intensity detected by SONG instrument during 1994, March–June in geographical coordinates.

Analyzing SONG instrument data we found that at high latitudes ($L > 4.5$) the count rate during Forbush event (April 17) was significantly lower than before and after it (April 16 and 18). However, at middle latitudes ($2 < L < 3$) SONG instrument's count rate, especially at the beginning of the Forbush event was higher than before and after it. To study the phenomena more carefully we analyzed the mean count rate of the SONG instrument in the polar caps and at middle latitudes (from $L = 2.1$ to 2.9, mean $L \approx 2.5$, since in this interval of L the latitude dependence of the count rate is linear) for each orbit. To take the longitude dependence into account, we normalized the data obtained at middle longitudes during the two time intervals analyzed (from April 1 to 5 and from April 15 to 18, 1994) to the mean data at different longitudes obtained during April 5–14. Moreover, we used mean values of the count rates obtained during the local day time and the local night time separately for the Northern and the Southern Hemispheres.

3. Results

The time dependence of SONG instrument's count rate obtained in the polar caps and at middle latitudes in the Northern and in the Southern Hemispheres, and different NM data (hourly data) during four days around the Forbush events April 17, 1994 (April 15–18) and April 3, 1994 (April 1–4) are presented in Fig. 2(a and b). To compare our data with ground NM data we normalized both SONG instrument's and NM data obtained during

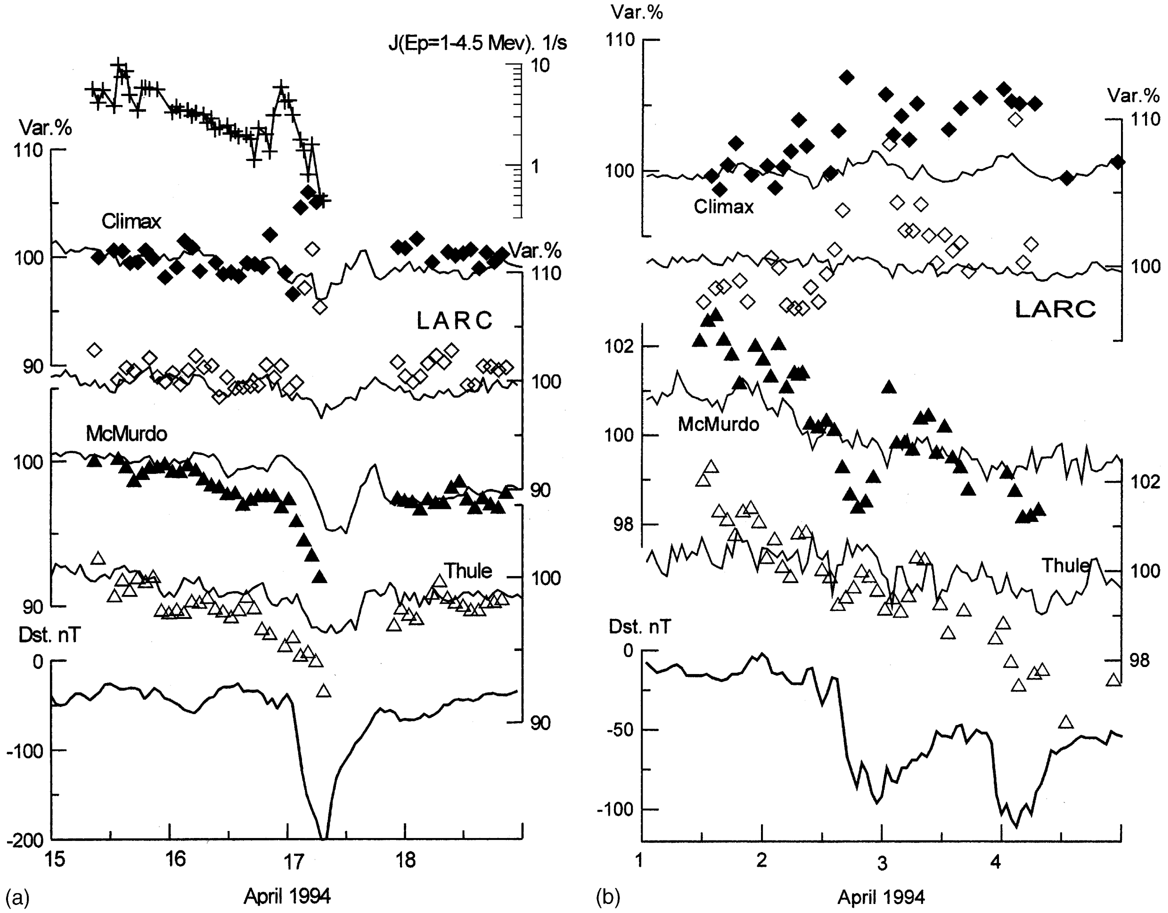

Fig. 2. Time dependence of SONG instrument's count rate obtained in the polar caps and at the middle latitudes in the Northern and in the Southern Hemispheres and different NM data during the Forbush events of April 17, 1994 (a), and April 3–4, 1994 (b).

April 15–18 to the mean background count rates obtained during 10 days before April 15. Since the cosmic ray flux gradually decreased from the middle of March, 1994 until the beginning of April, 1994 we could not use the mean values obtained before April 1–4 as background conditions. To compare the data obtained in the beginning of April with the NM data, we normalized both SONG instrument's and NM data to mean background count rates obtained for these four days (April 1–4). We compared SONG instrument's data obtained in the Northern polar cap (open triangles) with those of the North-polar Thule NM and those in the Southern polar cap (closed triangles)—with those of the South-polar McMurdo NM. At middle latitudes in the Southern Hemisphere (open diamonds), SONG data are compared with those of LARC NM, situated in Antarctica (King George Island, cut-off rigidity $R = 3.06$ GV for 1990 and $R = 2.97$ GV for 1995, Storini et al., 1999), while in the Northern Hemisphere (closed diamonds)—with Climax NM data (cut-off rigidity $R = 2.99$ GV). At the bottom of Fig. 2a and b time histories of the D_{st} index (in nT) for these Forbush events time intervals are shown. Besides that, for April 17 event, we have the opportunity to show the time dependence of the proton flux ($E_{\mathrm{p}} = 1$–4.5 MeV) in counts/s (crosses), also measured in the experiment onboard "CORONAS-I" satellite (Kuznetsov et al., 1995). These data permit us to estimate shock wave region.

From Fig. 2 we can see that data obtained both by the SONG instrument and by NMs at middle and high latitudes during both events are different, but the difference between middle and high latitudes of SONG instrument's data is significantly stronger than that for NMs data. During the April 17 event the Thule and McMurdo data vary (4% and 5%, respectively) corresponding to an 8% variation in "CORONAS-I" data. It may be connected with differences in minimal energy of particles detected by Thule and McMurdo NMs (~500 MeV) and "CORONAS-I" (~70 MeV). We notice that both the SONG instrument and NMs detected the beginning of the Forbush effect at the north earlier than at the south and in the south the decrease was more gradual. It was found that at high latitudes SONG instrument data obtained both in the Southern and in the Northern caps well correlate both with D_{st} index and polar NMs data (correlation coefficients values are R(SONG—the Northern cap, D_{st}) = 0.73, R(SONG—the Northern cap, Thule) = 0.88, R(SONG—the Southern cap, D_{st}) = 0.86, R(SONG—the Southern cap, McMurdo) = 0.87.

At middle latitudes, SONG instrument and NM data obtained during the Forbush event of April 17 are very different. Mid-latitude neutron monitors show a weaker event than polar NM—the range of NM decrease measured by Climax and LARC is ≈4%, but these maximal values were detected only for a very short time. Data obtained using the SONG instrument at $L = 2.1$–2.9 show a significant enhancement—≈7–8% and ≈8–10% in the Northern and Southern Hemispheres, respectively. So there was no correlation of SONG instrument's data with that NM of at the middle latitudes, and there was the anticorrelation with D_{st} index and polar NM data (R(SONG—middle latitudes north, D_{st}) = −0.8, R(SONG—middle latitudes south, D_{st}) = −0.88).

The Forbush effects observed during April 3–4 were significantly weaker than the one observed during April 17, but we can see the similar effect like that in April 17: the difference between middle and high latitudes for SONG instrument's data is significantly stronger than that for NM. There were no significant decreases observed by polar NMs, but SONG instrument detected some decreases. The ranges of the Thule and McMurdo data variations < 1% and ≈0.5% correspond to ≈1% during April 2, and ≈2.5% during April 4 in the SONG instrument data in the Northern polar cap and ≈1.5–2% in the Southern polar cap. We found that the high-latitude SONG data, obtained both in the Southern and in the Northern caps correlate well with both the D_{st} index and with the McMurdo NM data (R(SONG—the Northern cap, D_{st}) = 0.78, R(SONG—the Northern cap, Thule)=0.56, R(SONG—the Southern cap, D_{st}) = 0.85, R(SONG—the Southern cap, McMurdo) =0.83). It is clearly seen that neutron monitors data are more gradual than that of the SONG instrument.

At middle latitudes, SONG instrument and NM data obtained during the Forbush event of April 3–4 are also very different. Middle-latitude NMs practically do not show any Forbush effects, but only significant diurnal variations. Data obtained using the SONG instrument at $L = 2.1$–2.9 show a significant enhancement (≈8% in the Southern hemisphere and ≈7% in the northern one). So there was no correlation between SONG and NM data at middle latitudes and anticorrelation with D_{st}-variation as in the first case (R(SONG—middle latitudes north, D_{st}) = −0.79, R(SONG—middle latitudes south, D_{st}) = −0.74).

We suppose that such a difference in the data obtained at different latitudes with the help of SONG instrument and NM observed in both cases may be related to the response of the NM and the SONG instrument to different parts of cosmic ray energy spectra of particles detected by SONG instrument and neutron monitors or to a variation in the rigidity cut-off during geomagnetic storms. For example, Fluckiger et al. (1980) showed that during the initial phase of a geomagnetic storm ($D_{st} = -100$ nT) cut-off rigidity variations reached 15% in the interval from 2 to 3 GV. Similar results on rigidity cut-off variations were reported by Lockwood and Webber (1991). Such variations of the rigidity cut-off caused by the ring current development could have led to the enhancement of the cosmic ray flux detected by SONG instrument. Since latitude dependence of SONG instrument count rate is linear in the interval from $L = 2.1$ to 2.9, the values of count rate enhancement obtained at middle latitudes permit to roughly estimate the cut-off rigidity cut-off variations during the initial phase of the observed geomagnetic storms—8–10% for $D_{st} = -200$ nT and 7–8% for $D_{st} = -100$ nT.

To understand what conditions lead to each of these two events, we compare the time dependencies of all data shown in Fig. 2 (a and b). We can see that for the April 3–4 event the beginning of the proton ($E_p > 70$ MeV) and electron ($E_e > 55$ MeV) flux the decrease in the South cap, the increase at middle latitudes and the beginning of the of D_{st}-variation were observed at the same time. Since Forbush effects were not significant during the time period April 1–4, we cannot say exactly anything about the shock wave influence in this case.

During April 17 event, the beginning of the proton ($E_p > 70$ MeV) and electron ($E_e > 55$ MeV) flux decrease in the polar caps, the increase at middle latitudes and the decrease of the D_{st}-variation were also observed at the same time ~2 h UT April 17. The proton ($E_p = 1$–4.5 MeV) flux increase began earlier, at ~20 h, 30 min UT, April 16, when the beginning of magnetic substorm which was connected with first phase of the magnetic storm. This effect permits to suggest that the shock wave occurs probably during the magnetic storm first phase. The main phase of the magnetic storm, and Forbush effects was detected behind the shock wave. Unfortunately SSC or SI at ~20 h 30 min UT. April 16 were not observed.

4. Conclusions

The comparison of data obtained using the SONG instrument on board the low-altitude satellite "CORONAS-I" and at different ground NMs (Climax, LARC, McMurdo and Thule) during two time intervals of April 1994 with Forbush events in April 1994 showed that the proton ($E_p > 70$ MeV) and electron ($E_e > 55$ MeV) flux variations measured by the SONG instrument in polar caps are in a good agreement with the polar NM data. At middle latitudes during the decreasing D_{st} index, the cut-off rigidity variations were so strong that instead of Forbush effects the SONG instrument detected a significant enhancement of protons with energies > 70 MeV and electrons with energies > 55 MeV (which is probably caused by cut-off rigidity variations during initial phase of the observed geomagnetic storms, as discussed by Fluckiger et al., 1980). Combining the ground-based NM network data with low-altitude high-inclination satellite data from energetic particle devices with sufficient geometric factor is one of the possibilities to improve the knowledge of cosmic ray anisotropy, its spectra and connections to IMF and solar wind characteristics.

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