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TOPSIDE IONOSPHERE DURING SOLAR COSMIC RAY BURSTS AND FORBUSH DECREASES IN GALACTIC COSMIC RAYS

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Abstract. The paper considers the behavior of the upper ionosphere at heights of the F2 layer during Forbush decreases in galactic cosmic rays (GCR FDs) and solar cosmic ray (SCR) bursts. We use the results of long-term continuous observations of cosmic rays and the ionosphere in Novosibirsk for the period from 1968 to 2021. The ionospheric disturbances in the F2 layer during GCR FDs, which were accompanied by a magnetic storm, took the form of an ionospheric storm negative phase. The scale of the negative phase of the ionospheric F-layer disturbance increases with increasing *Dst* index of the geomagnetic storm. This increase in the amplitude of the ionospheric disturbance becomes more and more significant depending on the magnitude of Forbush decreases. A burst of the amplitude of the daily variation in the F2-layer critical frequency occurred eight days after SCR bursts and GCR FD front. We assume that this burst might have been caused by disturbances in the lower atmosphere due to significant variations in the intensity of SCR and GCR fluxes.

Keywords: solar cosmic rays, galactic cosmic rays, ionosphere, geomagnetic disturbance.

INTRODUCTION

The ionosphere is a highly ionized layer of the upper atmosphere. The main parameters of the ionosphere include electron density, ion content and temperature, which vary in a complex way with height. There are the following layers of maximum electron density: D (80 km), E (110 km), and F, divided into F1 (170 km) and F2 (300 km) [Alpert, 1972]. The height of the layers, their ion/electron and chemical content, and other parameters vary significantly with time, both regularly and sporadically.

Wolf numbers, which have been used for almost two centuries to find links between the level of solar activity and atmospheric conditions, describe only the general level of solar activity in an 11-year cycle, but do not reflect the amount of energy entering Earth's atmosphere during a particular solar disturbance. The strongest manifestation of solar activity is solar flares — sporadic explosive processes that cause sharp increases in fluxes of hard UV radiation, X-rays, and gamma rays, as well as energetic elementary particles of solar cosmic rays (SCRs). They, in turn, exert an impact on the magnetosphere, generating global magnetic disturbances, and on Earth's atmosphere, increasing ionization in all its layers, affecting the chemical composition and transparency. Therefore, the mechanisms of solar-terrestrial relations are usually studied by considering the intensity of solar radiation in visible and infrared regions, the intensity of solar X-rays and UV emission, fluxes of solar (SCRs) and galactic (GCRs) cosmic rays, the interplanetary magnetic field. During solar chromospheric flares when radiation of all kinds increases, there are sudden ionospheric disturbances manifested in an increase in electron density: in the D-region, up to several orders of magnitude; in the E-region, by 50–200 %; in the F-region, by 10–30 % [Mitra, 1977]. Kunitsyn et al. [2015] have analyzed sudden increases in the electron density in the upper atmosphere, using GNSS (Global Navigation Satellite System) data for a number of X-class solar flares occurring in solar cycles 23 and 24. The analysis has shown that the degree of impact on the ionosphere, determined by variations in the total electron content and the rate of its change, depends weakly on the X-ray flare intensity and is defined mainly by variations in hard UV radiation, which do not always correlate well with the X-ray flare intensity.

The long-term response of the E layer to solar X-ray flares was studied by Givishvili, Leshchenko [2022], using ground-based vertical sounding data from the station Moscow and five Japanese stations, from 1969 to 2015. The authors detected a long-term increase in X-ray contribution to the total E-layer ionization rate during the entire period of interest at a rate independent of solar cycle. They did not find a dependence of the trend rate on latitude (26°–56° N) and longitude (37°–128° E).

Using GPS and GLONASS data, Smirnov and Smirnova [2019] have examined the total electron content increment (DTEC) during solar flares that occurred at the maximum of solar cycle 23 (October 28, 2003) and minimum of cycle 24 (September 6, 2017) in the same season and at close solar zenith angles. It was shown that the positive DTEC burst was 1.5–2 min, the total duration of the response being ~10 min and independent of solar flare importance.

The results of observations of cosmic rays (CRs) and the ionosphere at F2-layer heights during Forbush decreases in GCRs and SCR bursts are discussed below.

DATA AND ANALYSIS

We have used results of observations made at the CR station Novosibirsk (24NM-64 neutron monitor data, 24 m^2) [http://193.232.24.200/nvbk/main.htm] and at the ionospheric station Novosibirsk (AIS/Parus ionosonde) [http://im.ipgg.sbras.ru] for the period from 1968 to 2021. We dealt with solar proton events (SPE) — CR bursts observed at the latitude of Novosibirsk (geomagnetic cutoff rigidity R_c=2.91 GV) as so-called Ground Level Enhancement (GLE). We analyzed the GLE events with an amplitude of 2.5 % or higher of the background level. The total number of such events for the given period was 18, five of which had an amplitude 2.5–4.5 %; five, 4.5–5.5 %; three, 5.6–9.5 %; two, 10–15 %; two, 20–30 %; and one, 127 %. The method of superimposed epochs (MSE) was used in the analysis. The SCR flare maximum was taken as the zero moment. The critical frequency f_oF2 is considered as a characteristic of the F2 layer. Figure 1 plots the distribution of daily averages and amplitude of diurnal variation of f_oF2 relative to an SCR burst for 18 GLE events.

Errors of averages are indicated by dashed lines. There is an increase in daily mean f_oF2 during the GLE and on the first day after it, whereas the diurnal variation amplitude (the difference between the daytime maximum and the nighttime minimum) from the GLE moment decreases sharply (blue lines in Figure 1, *b* are the mean amplitudes before and after the SCR burst). This difference is 12.5 %. The differences in the averages before and after the event are statistically significant according to the Student's criterion (the significance level p=0.05): calculated t=3.2 at degrees of freedom of 8 is greater than tabulated 2.3.

Penetration of SCR protons into the atmosphere causes a disturbance in the ionosphere, known as polar cap absorption (PCA). PCA is typical for high latitudes, where low-energy solar protons from 10 MeV can freely penetrate into the atmosphere due to solar flares [Driatsky, 1974]. In the events of interest, the solar flares produced protons with energy significantly exceeding the geomagnetic cutoff threshold (2.91 GV) of the midlatitude station Novosibirsk. There is a kind of expansion of the auroral zone, where disturbances occur across the thickness of the ionosphere. During disturbances, the behavior of the F2 layer is usually represented as an absolute (in MHz) or relative (in %) difference between f_oF2 during the storm and that during the quiet days (or monthly median) selected [Danilov, 2013]:

$$\delta f_o\mathrm{F2}=[f_o\mathrm{F2}_{\mathrm{observed}}-f_o\mathrm{F2}_{\mathrm{med}}]/f_o\mathrm{F2}_{\mathrm{med}}.$$

Figure 2 shows relative variations in δf_oF2 during the SCR bursts recordered at midlatitudes (for 18 GLE events).

PCA is characteristic of the D layer, where the electron density can increase by two orders of magnitude [Mitra, 1977]. The F layer exhibits both increases and decreases in f_oF2, and hence in the electron density (Figure 2). The increase in the F2-layer critical frequency coincides with the moment of the maximum SCR burst and is more than 7 %. The generation of SCRs during flares is usually accompanied by a significant increase in UV intensity in various spectral intervals, the 55–65 and 85–95 nm UV radiation leading to a noticeable increase in the electron density, and 15–20 nm UV generating a negative disturbance of the F layer [Leonovich, Tashchilin, 2008; Leonovich et al., 2010]. It takes the UV radiation 8.5 min to reach Earth; SCRs, less than 1 hr. As a result, we can observe F-layer disturbances of both signs. Also noteworthy is the presence of a more significant increase in f_oF2 eight days later. The second increase is more pronounced and exceeds 13 %. Nonetheless, the second positive burst of f_oF2, clearly observed eight days later, is not the result of changes in the ionizing agent (UV).

Since 1968, the neutron monitor in Novosibirsk has observed 189 Forbush decreases in galactic cosmic rays (GCR FDs), 135 of which were accompanied and 54 were not accompanied by magnetic storms. All the events were analyzed depending on FD by dividing them into groups: 1 — with 2.5–4.5 % amplitude; 2 — with 5–7 % amplitude, 3 — with an amplitude of 8 %

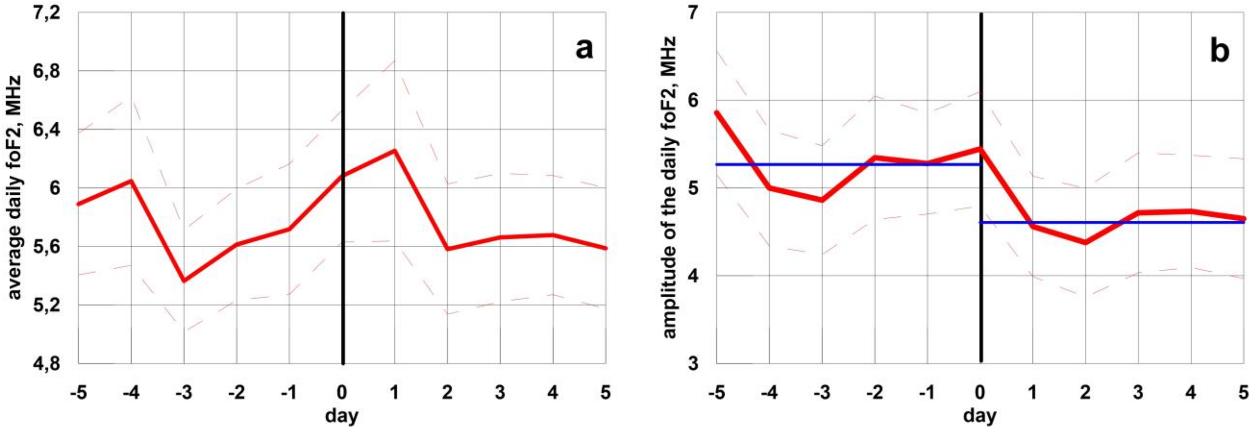

Figure 1. Distribution of daily averages (*a*) and diurnal variation amplitude (*b*) of the critical frequency f_oF2. Dashed lines are errors of averages

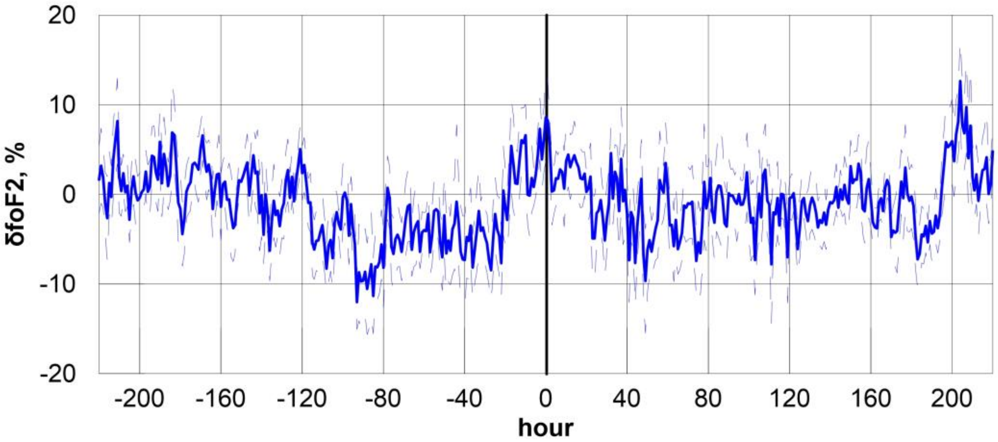

Figure 2. Variations in the F2-layer critical frequency during SCR bursts. Dashed lines are errors of averages

and higher. The FDs with geomagnetic storms were additionally grouped depending on the *Dst* index: 1 — *Dst*≥–100 nT; 2 — *Dst*=–100÷–150 nT; 3 — *Dst*≤–200 nT. MSE was also employed. The moment of detection of the GCR FD front was taken as zero. Relative variations in the F2-layer critical frequency during GCR FDs are illustrated in Figure 3.

Of the 54 FDs unattended by magnetic storms (Figure 3, *a*), 44 had a 2.5–4.5 % amplitude (curve 1); 7 events, 5–7 % (curve 2); 3 events, ≥8 % (curve 3). We can definitely say that there is no connection between the F2-layer critical frequency variations with FDs without magnetic storms only for the FDs with an amplitude to 5 % (curve 1).

Of 135 FDs accompanied by magnetic storms (Figure 3, *b*), 59 events had a 2.5–4.5 % amplitude (curve 1); 51 events, 5–7 % (curve 2); 25 events, an amplitude of ≥8 % (curve 3). The FD main phase often coincides with the magnetic storm main phase. The F2-layer response (Figure 3, *b*) manifests itself as a decrease in its critical frequency, which corresponds to a decrease in the electron density N_e. For all the 135 events, the ionospheric storm over Novosibirsk was observed only in the form of a negative disturbance. Note that the dynamics of the disturbance repeats the profile of the Forbush effect of GCRs. With an increase in the GCR FD amplitude, the amplitude of the ionospheric disturbance also increases (Figure 3, *b*): at 2.5–4.5 % FD, the depth of the decrease in f_oF2 during the ionospheric storm negative phase turns out to be equal to 13 % (curve 1); at 5–7 % FD, 15 % (curve 2); and at ≥8 % FD, >22 % (curve 3). GCR FDs can be accompanied by geomagnetic storms of any intensity. Figure 4 shows disturbances in the F2 layer for geomagnetic storms with different *Dst* indices, which attended GCR FDs of different amplitudes.

The depth of the decrease in f_oF2 and hence in the F-layer electron density during the disturbance negative phase increases with *Dst* (Figure 4). The increase in the ionospheric disturbance amplitude is becoming more and more significant depending on the FDs attended by these geomagnetic storms.

Figure 5 illustrates distributions of daily averages and diurnal variation amplitude of f_oF2 relative to the GCR FD front.

DISCUSSION

The maximum of the ionospheric storm negative phase occurs on the first day after the passage of the FD front (Figure 5, *a*); and after a few (3–4) days, the ionosphere practically returns to pre-storm conditions. Of special note, however, is the behavior of the amplitude of the diurnal variation in the F2-layer critical frequency (Figure 5, *b*). Eight days later, there is a sharp increase in the amplitude of the diurnal variation in f_oF2. This burst is seen both for the FDs without geomagnetic storms (curve 1) and for those with geomagnetic storms (curve 2). The sharp increase in the amplitude of the diurnal variation in f_oF2 is 1.7–2 MHz, which corresponds to 32–40 %.

The ionospheric storm negative phase is thought to be caused by changes in the thermospheric gas composition due to heating of the thermosphere by ionospheric currents during geomagnetic disturbances. This mechanism was first proposed by Seaton [1956]. Being maximum in the F2 layer, the electron density N_e turns out to be almost proportional to the ratio [O]/[N_2] [Mikhailov et al., 1995]. The movement of the negative ionospheric disturbance is driven by strong meridional winds, which are generated in the polar region and are equatorward.

During the geomagnetic storm main phase, the ionospheric disturbance negative phase is usually changed to a positive one [Danilov, 2013]. Several mechanisms have been proposed for the formation of the ionospheric storm positive phase [Danilov, Belik, 1992; Prolss, 1995]: a rise of the F2 layer due to vertical drift, plasma streams from the plasmosphere, downwelling of gas as a result of storm-induced thermospheric circulation. It is believed [Danilov, 2013] that the ionospheric storm positive phase is caused by traveling atmospheric disturbances carried by the equatorward meridional wind.

The thermospheric storm concept [Seaton, 1956; Rishbeth, Barron, 1960; Danilov, Belik, 1992; Prolss, 1995; Danilov, 2013; Ratovsky et al., 2018] suggests that the main factors in the formation of the ionospheric response are the thermosphere composition and wind disturbances caused by heating of the high-latitude thermosphere. Statistical analysis and simulation [Ratovsky et al., 2020] have shown that the responses of the high-latitude ionosphere during the recovery phase do not contradict the thermospheric storm concept. The simulation

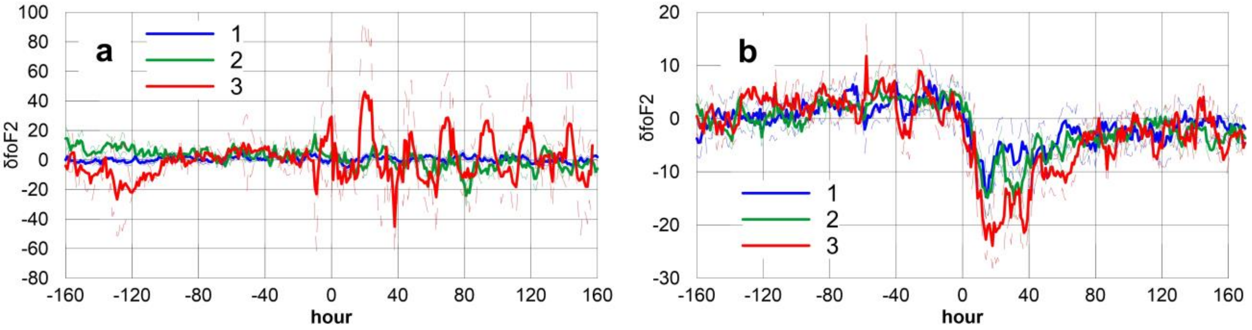

Figure 3. Variations in the critical frequency δf_oF2 during Forbush decreases with amplitudes 2.5–4.5 % (curve 1), 5–7 % (curve 2), and at least 8 % (curve 3), unattended (*a*) and attended (*b*) by magnetic storms. Dashed lines are errors of averages

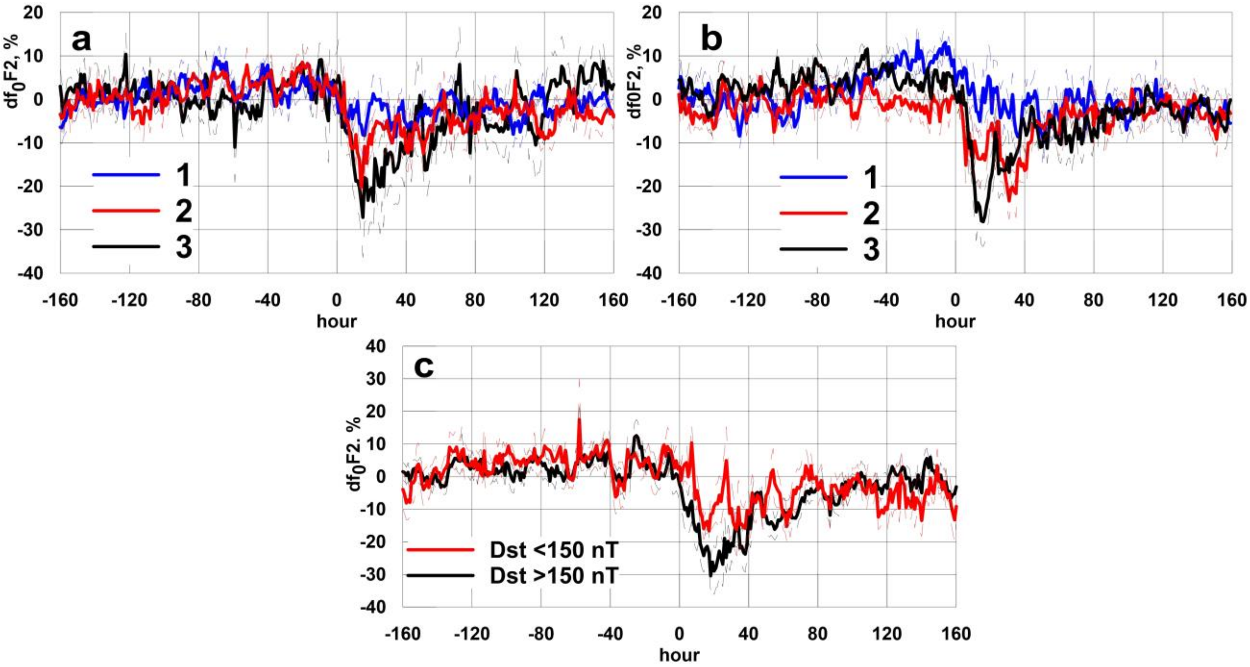

Figure 4. Variations in the F2-layer critical frequency during Forbush decreases in GCRs with amplitudes 2.5–4.5 % (*a*), 5–7 % (*b*), and at least 8 % (*c*), which were accompanied by geomagnetic storms with *Dst* indices ≥–100 nT (curve 1), –100÷–150 nT (curve 2), and a minimum of –150 nT (curve 3). Dashed lines are errors of averages

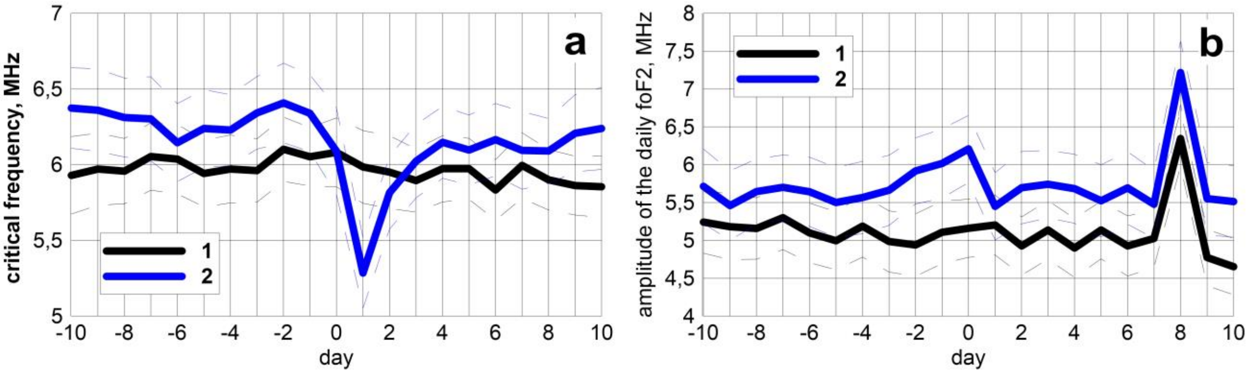

Figure 5. Distribution of daily averages (*a*) and diurnal variation amplitude of (*b*) of the F2-layer critical frequency relative to the front of the Forbush decrease in GCRs for FDs unattended (curve 1) and attended (curve 2) by geomagnetic storms. Dashed lines are errors of averages

results led to the conclusion that the presence of the strong positive response can be explained by the strong effect of the neutral wind during the geomagnetic storm main phase. The positive after-storm effects at different latitudes are caused by positive disturbances of the atomic oxygen density n(O). Chernigovskaya et al. [2021b] point out that the disturbances in the form of thermospheric molecular gas waves can play an important role in the dynamics of the mid-latitude ionosphere. These disturbances propagate from east to west for a few days after termination of the action of the magnetospheric source. The longitudinal irregularity of the ionospheric effects caused by thermospheric molecular gas waves has been revealed by analyzing data from the mid-latitude Eurasian chain of vertical sounding ionosondes [Chernigovskaya et al., 2021a].

Danilov [2013] also points out that some effects such as the prolonged positive phase at midlatitudes and the negative phase at low latitudes, observed during severe ionospheric storms, cannot be attributed to the horizontal dynamics and variations of the neutral composition. Perhaps, when considering the mechanism of formation of an ionospheric storm, it is necessary to take into account other, fundamentally different groups of processes.

Note that not all of the events (GCR FDs) considered were accompanied by geomagnetic storms. Almost a third of the Forbush decreases (54 events) as well as SCR bursts were not accompanied by magnetic storms. Nonetheless, after all the events there was a sharp increase in the amplitude of the diurnal variation in the F2-layer critical frequency.

The ionosphere is affected not only by ionization sources, variations in the intensity of which are caused by processes on the Sun and in Earth's magnetosphere. It is also affected by the lower atmosphere. The F2-layer parameters may also change due to changes in the neutral composition of the medium and dynamic processes in it [Danilov, Laštovička, 2001]. In the troposphere and stratosphere at heights from ~3 to 60 km, the main source of ionization is cosmic rays whose intensity depends on solar activity. In the atmosphere, GCR ionization maxima are at 10–20 km; and SCR ones, at 20–60 km [Bazilevskaya, 2005]. Cosmic ray variations cause changes both in the chemical composition of the atmosphere and in characteristics of aerosol particles [Lushnikov et al., 2014], thereby altering the atmosphere transparency [Kudryavtsev, Junger, 2011] and the cloud cover [Raspopov, Veretenenko, 2009]. Changes in the optical properties of the atmosphere modulate the solar energy entering the atmosphere, which, in turn, causes the thermobaric regime of the atmosphere to change and circulation to increase [Veretenenko, Thejll, 2004, 2005].

CONCLUSION

When SCRs are generated in solar flares, the UV intensity increases in various ranges; therefore, during recording of SCR bursts on Earth, not only the PCA-type effects in the D layer, but also disturbances of the electron density (and, accordingly, the critical frequency) of both signs in the F2 layer are observed.

The ionospheric disturbances in the F2 layer during Forbush decreases in GCRs attended by magnetic storms occur in the form of the ionospheric storm negative phase. With an increase in the FD amplitude, the ionospheric disturbance amplitude also increases. GCR FDs can be accompanied by geomagnetic storms of any intensity. The depth of the f_0F2 decrease during the F-layer disturbance negative phase increases with *Dst*. The increase in the amplitude of the negative ionospheric disturbance becomes more and more significant depending on the Forbush decreases that are accompanied by these geomagnetic storms.

Within eight days after the recording of the SCR bursts and the front of the Forbush decrease in GCRs, there was a sharp increase in the amplitude of the diurnal variation in the F2-layer critical frequency.

We can assume that the burst of f_0F2 and its diurnal variation amplitude observed on the eighth day was induced by the disturbances in the lower atmosphere, which might have been caused by significant variations in the intensity of SCR and GCR fluxes.

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