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Cyclic changes in the lower ionosphere parameters and their variations during solar flares according to data on natural ELF–VLF emission

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Abstract. Analysis of experimental data for solar cycle variations in the response of natural ELF–VLF emission intensity to sudden ionospheric disturbances, as well as of low-frequency electromagnetic fields calculated by a model of a flat waveguide with a sharp upper boundary, reveals the existence and character of solar cycle variations in the D region parameters. Both quiet conditions and sudden ionospheric disturbances are considered. The results for the ELF–VLF emission are compared with the results obtained by other authors.

1. Introduction

The dependence of the lower ionosphere parameters on solar activity has already been studied during several decades. However, the problem has not been solved yet. *Smirnova and Danilov* [1998] analyzed the conclusions made by a number of authors concerning the dependence of the quiet-time D region electron concentration on solar activity. *Danilov et al.* [1995], *Friedrich and Tokar* [1992, 1997], *Knyazev et al.* [1994a, 1994b], *Mechtly et al.* [1972], and *Sengupta* [1980] considered the results of direct measurements of electron concentration and empirical models of the D region relying on these measurements. *Bremer and Singer* [1977] and *Lauter et al.* [1976] considered the patrol of the D region state by the radio wave propagation method (measurements of the radio wave absorption by the A1 and A3 methods, measurements of the reflection altitude h_p). *Smirnova and Danilov* [1998] emphasize that different authors present substantially different amplitudes of increase in the electron concentration of the upper D region with solar activity and conclusions made by different authors on the sign of the solar activity effect in the lower D region also contradict each other.

Detection of the intensity of natural low-frequency electromagnetic emission propagating in the near-Earth waveguide is an easy method for continuous monitoring the D region condition. This paper describes the studies of variations in the lower ionosphere parameters with solar activity involving the analysis of solar cycle variations in the response of the regular noise background (RNB) of natural low-frequency (0.5–10 kHz) emission to solar flares inducing sudden ionospheric disturbances (SID). The RNB is a fluctuating component of the electromagnetic emission generated by lightning discharges and propagating in the near-Earth waveguide [*Druzhin and Shapaev*, 1988; *Druzhin et al.,* 1986; *Kozlov and Mullayarov*, 1996; *Vershinin and Ponomarev,* 1966]. The character of solar cycle changes of natural low-frequency emission variations during solar flares is the evidence of existence of solar cycle variations in both the quiet-time D region parameters and their response to solar flares.

2. Experimental Data

This paper considers the measurements of natural ELF–VLF (0.5–10 kHz) emission intensity at the Yakutsk station obtained in 1973–1986. The variations in the emission intensity during SIDs are analyzed. *Murzaeva* [1977] has found that the RNB enhancement in the ELF band (0.5–3.0 kHz) with a maximum at 0.5–0.8 kHz and RNB weakening in the VLF band (3–10 kHz) with a maximum at 4–6 kHz are observed during strong bursts of solar X ray emission. Changes

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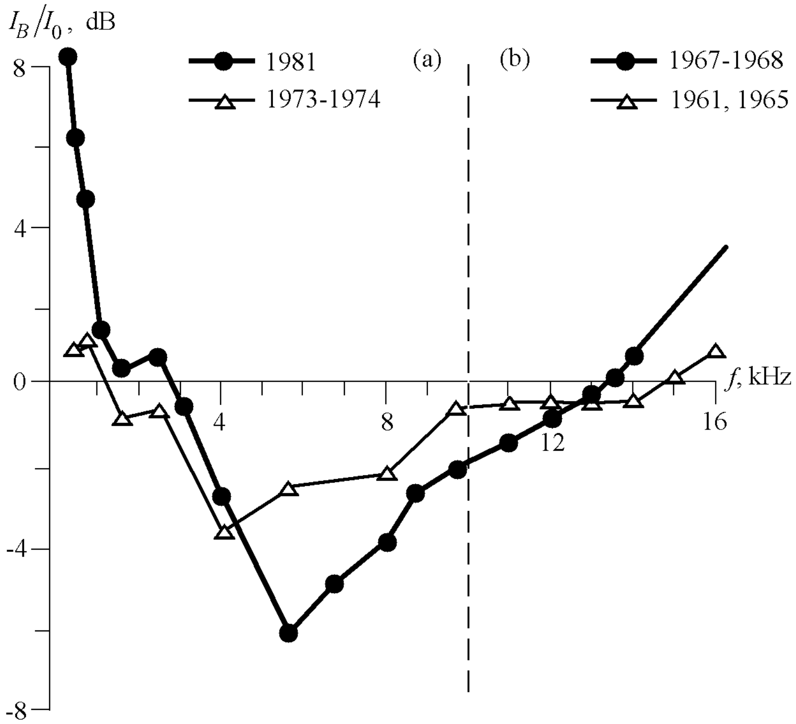

Figure 1. (a) Averaged variations in ELF–VLF emission intensity in the range from 0.5 to 10 kHz during SID. (b) Curves given in Figure 1a are extrapolated to the frequency range above 10 kHz by using the data of *Rizzo Piazza and Kauffman* [1975] on the frequency of transition from the VLF signal weakening to enhancement.

in the spectral distribution of the RNB intensity during a flare depend on the solar cycle phase [*Murzaeva,* 1997]. During the rise and maximum of the solar cycle, the maximum RNB intensity variations during SIDs in the ELF band and those in the VLF band are almost equal to each other, and during the fall period and minimum of the solar cycle the ratio between them is 1 : 3. In addition, during active-Sun periods, the frequency of transition from the signal enhancement to its weakening increases from 1–1.5 kHz to ~3 kHz (see Figure 1a).

3. Discussion

Our experiments have shown that there is a transition from an enhancement to a decrease in the RNB intensity during solar flares. During the solar cycle, the transition moves from 1.5 kHz for the periods of solar activity decline and minimum to ~3 kHz for the periods of solar activity rise and maximum.

It is known that in the frequency range above 10 kHz, i.e., outside the operating range of our equipment, there exists an inverse transition [*Eryushev*, 1960; *Field*, 1970; *Mitra*, 1977; *Sao et al.,* 1970]. It is worth analyzing its dependence on solar activity. Since we could not get the necessary experimental data, we extrapolated the experimental data obtained to the range above 10 kHz. The data obtained by *Rizzo Piazza and Kauffman* [1975] were used for the extrapolation.

Rizzo Piazza and Kauffman [1975] analyzed the measurements of amplitudes and phases of VLF signals from the Omega system transmitters in the 10.2–24 kHz band (adjacent to the band from 0.5 to 10 kHz which is considered in this paper) during the SIDs observed in the periods of active (1967, 1968) and quiet (1961–1965) Sun. It has been found that, during the quiet-Sun years, the VLF emission amplitude increases during solar flares mainly at the frequencies above ~15 kHz and decreases at the frequencies below this value. During the years of the active Sun, this transition takes place at 13.6 kHz. Figure 2 shows the variations in amplitudes and phases of signals from the VLF transmitters during the solar flares observed on 30 May 1967 (active Sun) and 13 April 1974 (quiet Sun) [*Rizzo Piazza and Kauffman*, 1975]. Figure 2 shows that the signal phase variations were observed during both flares. At the same time, the amplitude decrease was observed only during the quiet-Sun period on 13 April 1974.

Thus, we have drawn Figure 1b, using the results obtained by *Rizzo Piazza and Kauffman* [1975], that is, extrapolating the curves shown in Figure 1a over points to 15 kHz for quiet period and 13.6 kHz for active period. To justify the use of the data for 1967 in processing the data for 1981 (the curve in Figure 1a), the following arguments were used. Exact values of the transition frequencies may vary from one solar cycle to another. The important thing is that the reverse transition frequency decreases with solar activity rise. The latter fact has been revealed from the data for 1961, 1965 and 1967, 1968 and then confirmed by the data for 1974. During the latter year the transition frequency increased again, and the records of signal amplitude during the 13 April 1974 flare exhibited a negative bay at the 13.6-kHz point which has not been observed in 1967 [see *Rizzo Piazza and Kauffman*, 1975, Figure 2]. Therefore, one can see that the transition frequencies obtained by Rizzo Piazza and Kauffman in 1961, 1965 and 1974 are similar to each other, and the 15-kHz point taken from the data of 1961 and 1965 may be used in combination with the curve measured in 1973–1974. A reason for this operation is also the fact that the data on natural signal (RNB) variations during 1973–1974 comply with the observations in 1983-1986 [*Murzaeva*, 1997]. This fact provides an additional evidence of a constancy of the forward (from a rise to a decrease) and reverse (from a decrease to a rise) transition frequencies.

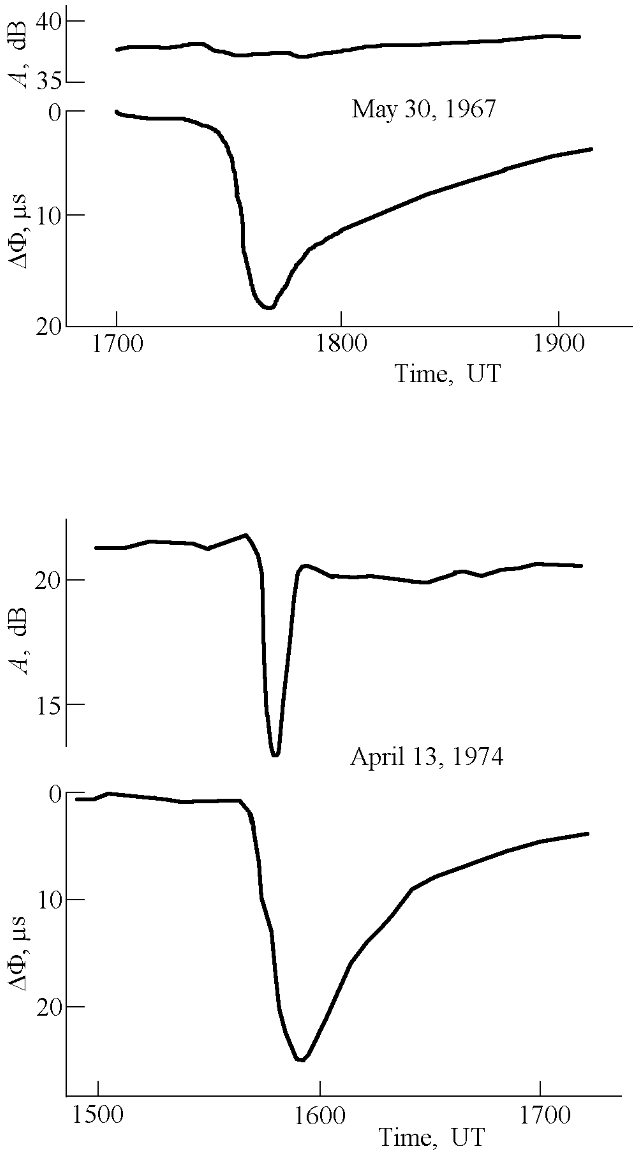

Figure 2. Two typical strong SIDs observed at 13.6 kHz. (top) Event that took place on Omega (Haiku)–Sao Paulo path (d = 12.9 Mm) when the Sun was active, and nearly no effect was found in amplitude. (bottom) Event on Omega (NDAK)–Sao Paulo path (d = 9.35 Mm), showing important amplitude fading under the quiet Sun conditions [*Rizzo Piazza and Kauffman*, 1975].

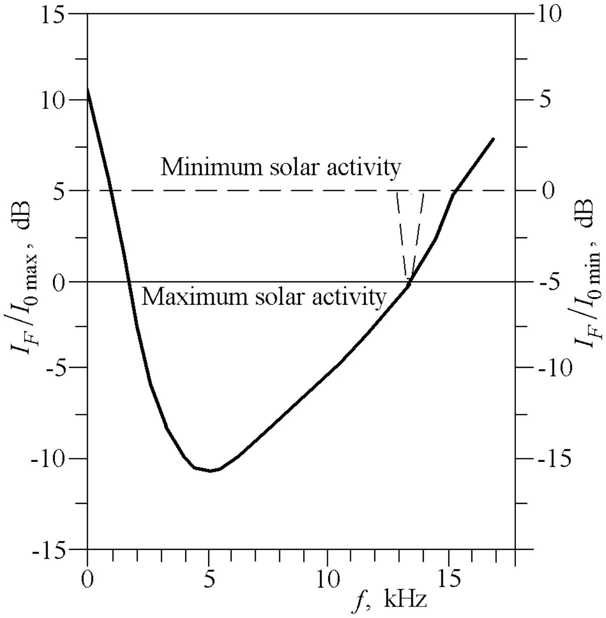

Figure 3. Scheme of solar cycle changes in the spectral distribution of variations in the natural ELF–VLF (0.5–10 kHz) emission intensity and in transmitter signals (13.6 kHz and 15 kHz) during SIDs.

Figures 1a and 1b demonstrate that during a solar cycle, not only the ratio between amplitudes of the signal increase (in the ELF band) and decrease (in the VLF band) changes during a SID, but also a narrowing of the band where the decrease in the VLF emission amplitude is observed occurs. During quiet-Sun periods the width of this band is ~13.5 kHz (from ~1.5 kHz to 15 kHz), and during the periods of active Sun it shrinks to ~10.5 kHz (from ~3 kHz to ~13.6 kHz). These variations are sketched in Figure 3. Signal variations measured from the upper zero line correspond to the quiet-Sun periods, and those measured from the lower zero line correspond to the active-Sun periods. During the period of low solar activity, the frequency 13.6 kHz belongs to the band where the signal amplitude decreases during SIDs. When solar activity is maximum, the amplitude does not change at this frequency, because in this case it is just the frequency of transition from the signal amplitude decrease to its increase. This looks like a displacement of an axis from which the radio emission intensity variations during solar flares at different levels of solar activity are measured. The displacement leads to variations in the ratio between the maximum amplitudes of the increase and decrease in the ELF–VLF emission and to narrowing of the

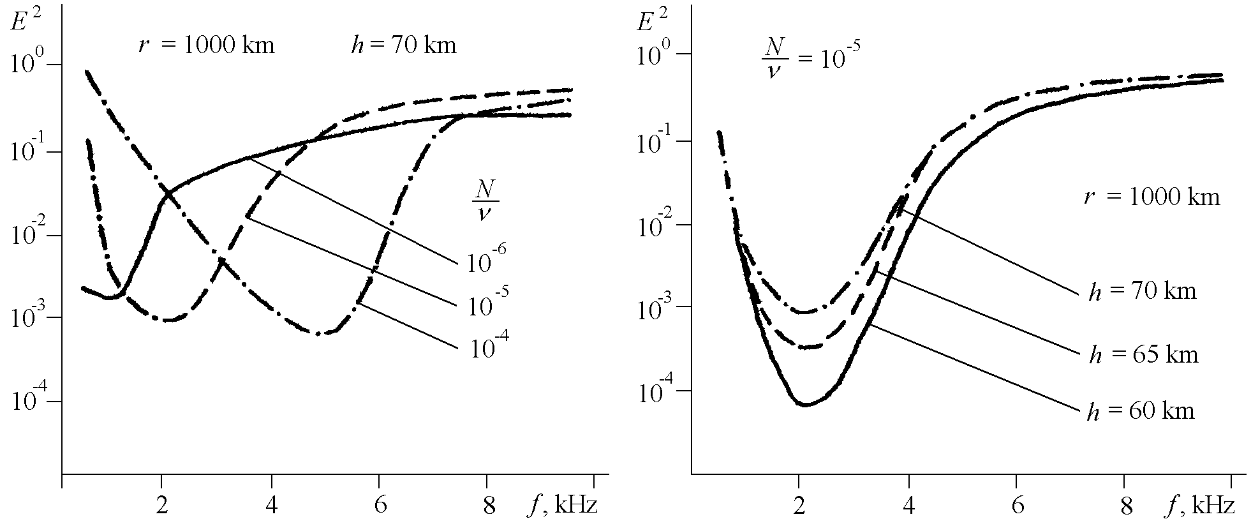

Figure 4. Calculated spectral distribution of E^2 of the ELF–VLF emission for different altitudes and conductivities of the upper wall of the flat waveguide with a sharp upper boundary.

band in which the emission is weakened. This effect apparently arises from solar cycle changes in the quiet-ionosphere conditions as well as in its response to solar X ray bursts.

In order to reveal solar cycle variations in the D region parameters and in their response to SIDs, we used the calculations of the field strength of low-frequency (0.5–10 kHz) emission propagating in the near-Earth waveguide obtained by the model of a flat waveguide with a sharp upper boundary suggested by D. S. Fligel' [*Alpert et al.,* 1967; *Murzaeva,* 1991; *Murzaeva and Fligel',* 1980]. In this model the Earth's conductivity is infinite and conductivity of the upper wall of the near-Earth waveguide is determined by the factor N/ν, where N is the electron concentration in cm^{-3}, and ν is the effective collision frequency in s^{-1}. The distance to the emission source is assumed to be 1000 km. The emission source power is 1 kW. The calculations were carried out using the mode theory. The calculations involved only the mode $n = 0$, because other modes scarcely contribute to the field strength at the distance $r \sim 1000$ km. The field strength was calculated for a wide range of variations in the ionospheric conductivity and altitude. In case of quiet ionosphere, the parameters were typically taken as follows: $N/\nu = 10^{-5}$ and the waveguide altitude $h = 70$ km [*Murzaeva,* 1991].

Figure 4 presents the calculations of $E^2(f, r)$ versus frequency for $N/\nu = 10^{-6}$, 10^{-5}, and 10^{-4} and $h = 70$, 65, and 60 km. Analyzing various combinations of changes in h and N/ν, we revealed two extreme situations: (1) if the altitude of the upper wall of the near-Earth waveguide ($h = 70$ km) remains constant, and N/ν varies from 10^{-6} (prior to the flare) to 10^{-4}, the variations in the ELF and VLF emission intensity are consistent with the experimental data for the active-Sun periods (see Figure 5, thick line); and (2) if the ratio $N/\nu = 10^{-5}$ remains constant during the flare, and h changes from 70 to 60 km, the variations in the emission intensity are similar to those in the RNB during the quiet-Sun periods. However, a better agreement was obtained when N/ν was assumed to increase 2–3 times (see Figure 5, thin line). In real situations, both h and N/ν vary during the flare. Nevertheless, the rough approximation allows us to assume that (1) the quiet-time ionospheric conductivity at the altitude of the upper wall of the near-Earth waveguide, which is determined by the N/ν ratio, is higher during the quiet-Sun periods than during the active-Sun years (this coincides with the conclusion of *Friedrich and Tokar* [1997], *Knyazev et al.* [1994a], and *Smirnova et al.* [1984] that the electron concentration in the lower D region decreases with increasing solar activity); and (2) during the flares inducing SIDs, a considerable increase in the conductivity of the upper wall of the near-Earth waveguide is observed in the active-Sun periods contrary to the periods of quiet Sun during which a more significant decrease in the near-Earth waveguide upper wall height is observed.

The character of the near-Earth waveguide parameter variations revealed in this work is similar to that obtained by *Trista and Lastovichka* [1970, 1972]. They found that a decrease in the near-Earth waveguide height leads to a SDA (sudden decrease of atmospherics) occurrence, whereas an increase in the conductivity causes SEA (sudden enhancement of atmospherics). Our calculations show that during quiet-Sun periods the number of SEA are much lower the number of SDA and even negligible, whereas during active-Sun periods the number of SEA increases sharply.

Conclusions

The comparative analysis of experimental data and calculations performed using the model of a flat waveguide with a sharp upper boundary showed that the quiet-ionosphere ratio N/ν at the upper boundary of the near-Earth waveguide

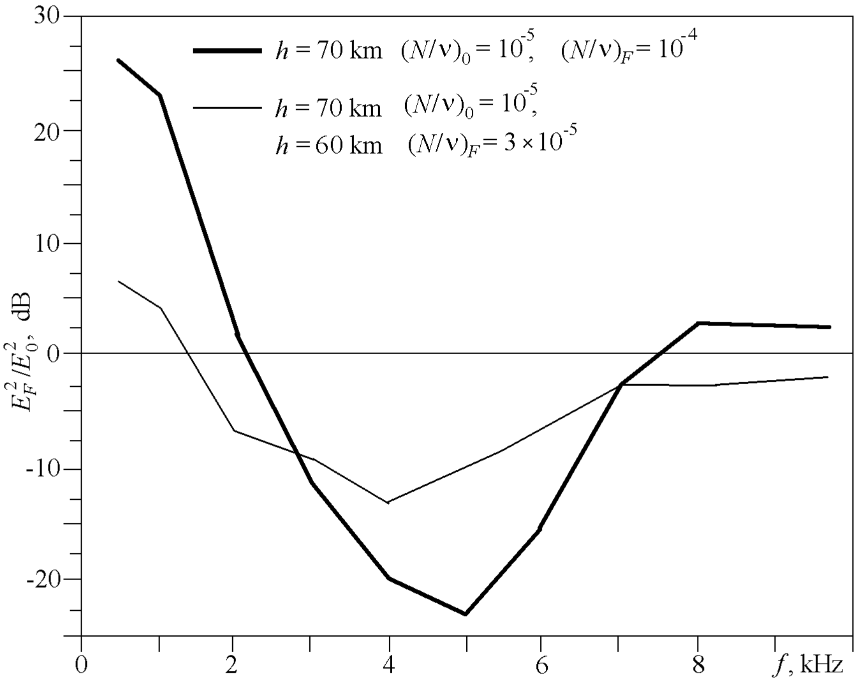

Figure 5. Calculated variations in the ELF–VLF emission intensity under the conditions similar to SIDs.

is higher at the quiet-Sun periods than at the active-Sun periods.

During the periods of sudden ionospheric disturbances, the increase in the conductivity of the upper boundary of the Earth-ionosphere waveguide is greater during the rising phase and maximum of the solar cycle. At the same time the variations in the waveguide upper boundary height are, apparently, more important during the falling phase and minimum of the solar cycle.

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References

Alpert, Ya. L., E. G. Guseva, and D. S. Fligel', *Electromagnetic Wave Propagation in the Earth-Ionosphere Waveguide (in Russian)*, 65 pp., Nauka, Moscow, 1967.

Bremer, J., and W. Singer, Diurnal, seasonal, and solar-cycle variations of electron densities in the ionospheric D and E regions, *J. Atmos. Terr. Phys., 39*, 25, 1977.

Danilov, A. D., A. Yu. Rodevich, and N. V. Smirnova, Problems with incorporating a new D region model into the IRI, *Adv. Space Res., 15*(2), 165, 1995.

Druzhin, G. I., and V. I. Shapaev, Role of global thunderstorm activity in formation of regular noise background, *Geomagn. Aeron. (in Russian), 28*, 81, 1988.

Druzhin, G. I., T. V. Toropchinova, and V. I. Shapaev, Regular noise background in VLF emission and global thunderstorm centers, *Geomagn. Aeron. (in Russian), 26*(2), 258, 1986.

Eryushev, N. N., On variations in parameter $(N/\nu)_{\mathrm{eff}}$ in the lower ionosphere during solar flares, *Izv. Krym. Astrofiz. Obs. (in Russian), 23*, 129, 1960.

Field, E. C., VLF and ELF propagation during sudden ionospheric disturbances, *J. Geophys. Res., 75*, 1927, 1970.

Friedrich, M., and K. M. Tokar, An empirical model of the nonauroral D region, *Radio Sci., 27*(6), 945, 1992.

Friedrich, M., and K. M. Tokar, New models of D region electron densities and related parameters, paper presented at the PRIME/IRI Workshop, Kuelungsborn, Germany, May 27–31, 1997.

Knyazev, A. K., L. V. Korneeva, V. N. Avdeev, and L. B. Vanina, Specification of the empirical model of relationship between the D region electron density and solar zenith angle by using rocket-borne measurements, *Geomagn. Aeron. (in Russian), 34*(5), 163, 1994a.

Knyazev, A. K., L. B. Vanina, L. V. Korneeva, and V. N. Avdeev, Profiles $N_e(e)$ in the equatorial lower ionosphere at solar minimum and maximum, *Geomagn. Aeron. (in Russian), 34*(1), 152, 1994b.

Kozlov, V. I., and I. A. Mullayarov, Observations of the thunderstorm activity in Yakutia in 1993–1994, *Meteorol. Gidrol. (in Russian), 2*, 105, 1996.

Lauter, E. A., et al., Middle atmosphere processes and lower ionosphere in winter, *Rep. HHI-STP*, 7, ZISTR, Berlin, 1976.

Mechtly, E. A., S. A. Bowhill, and L. G. Smith, Changes of lower ionosphere electron concentration with solar activity, *J. Atmos. Terr. Phys, 14*(6), 1165, 1972.

Mitra, A., *Effect of Solar Flares on the Earth's Ionosphere*, 370 pp., Mir, Moscow, 1977.

Murzaeva, N. N., Regular noise background of VLF emission during solar flares, in *Coupling of VLF Emission in the Upper Atmosphere with Other Geophysical Phenomena (in Russian)*, pp. 21–34, Akad. Nauk SSSR, Yakutsk, 1977.

Murzaeva, N. N., Variations in ELF–VLF emission intensity during solar flares, *Ph.D. Thesis (in Russian)*, 133 pp., Inst. of Sol.-Terr. Phys., Irkutsk, Russia, 1991.

Murzaeva, N. N., Solar-cycle changes of variations caused by solar flares in intensity of the regular noise background of natural ELF–VLF emission, in *Conference on Modern Problems of Solar Cyclicity, Abstracts (in Russian)*, p. 66, St. Petersburg, Russia, 1997.

Murzaeva, N. N., and D. S. Fligel', On effect of solar flares upon spectral characteristics of continuous low-frequency emission, in *Studies of Structure and Wave Properties of the Near-Earth Plasma (in Russian)*, p. 24, IZMIRAN, Moscow, 1980.

Rizzo Piazza, L., and P. Kauffman, Change of low ionosphere characteristics with solar cycle deduced from solar flare effects at VLF, *J. Atmos. Terr. Phys., 37*, 1281, 1975.

Sao, K., M. Yamashita, S. Tanahashi, H. Jindoh, and K. Ohta, Sudden enhancements (SEA) and decrease (SDA) of atmospherics, *J. Atmos. Terr. Phys., 32*, 1567, 1970.

Sengupta, P. R., Solar X ray control of the *D* region of the ionosphere, *J. Atmos. Terr. Phys., 42*, 339, 1980.

Smirnova, N. V., and A. D. Danilov, Solar activity effects in the ionospheric *D* region, *Geomagn. Aeron. (in Russian), 38*, 92, 1998.

Smirnova, N. V., Shch. F. Ogloblina, and V. A. Vlaskov, Models of the electron concentration of the ionospheric *D* region, *Preprint PGI-84-08-36 (in Russian)*, 31 pp., Akad. Nauk SSSR, Apatity, 1984.

Triska, P., and J. Lastovichka, On the sudden decrease of atmospherics on 5 kHz, *Geophys. Sbornic, XVIII*, p. 463, 1970.

Triska, P., and J. Lastovichka, Sudden decrease of atmospherics at 5 kHz, *J. Atmos. Terr. Phys., 34*, 1065, 1972.

Vershinin, E. F., and E. A. Ponomarev, On classification of continuous ULF emission in the upper atmosphere, in *Terrestrial Magnetism, Auroras, and Ultra-Low-Frequency Emission (in Russian)*, no. 1, p. 35, SibIZMIR, Irkutsk, Russia, 1966.

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