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Small-scale plasma inhomogeneities and correlated ELF emissions in the ionosphere over an earthquake region

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Abstract—Cosmos-1809 satellite data on ELF emissions, plasma density, N_e and variations dN_e in the ionosphere above the Spitak earthquake zone during a period of enhanced aftershock activity are presented. The data show that small-scale plasma inhomogeneities with $dN_e/N_e \approx 3$–8% and with a characteristic scale of 4–10 km along the orbit are excited on geomagnetic field tubes connected to the epicentral region, simultaneously with earthquake related ELF emissions. A generation mechanism for such inhomogeneities under the influence of seismic activity in terms of the dissipative instability of acoustic-gravity waves in the ionosphere is proposed. © 1997 Elsevier Science Ltd

INTRODUCTION

The results of ionospheric studies carried out recently by means of ground-based and satellite methods in regions of seismic activity have claimed the presence of lithosphere–ionosphere coupling during the precursor phases of earthquakes. A mechanism for this coupling could have an electromagnetic nature or be realized by means of acoustic-gravity waves; both mechanisms could act in parallel (Liperovsky *et al.*, 1992).

The ionospheric plasma disturbances connected with seismic activity have been studied mainly by means of vertical ionospheric soundings (Davis and Baker, 1965; Nestorov, 1979; Fatkullin *et al.*, 1989; Gokhberg *et al.*, 1988; Liperovsky *et al.*, 1992; Liperovskaya *et al.*, 1992). A number of perturbation effects in the ionosphere were revealed which arose some hours or days before the main shock. In particular, 2–3 days prior to an earthquake the critical frequency f_0F_2 of the night-time F-layer increases as compared to the median value and then it decreases 1 day before an earthquake. The maximum frequency difference between f_0F_2 and the median value reaches 2.8 MHz. The spatial scale of such disturbances is more than 1000 km (Liperovsky *et al.*, 1992).

The results of topside sounding of the ionosphere from the Intercosmos-19 satellite (Pulinets *et al.*, 1994) indicate that seismo-ionospheric disturbances appear as an upward motion of the F_2-layer, that is a decrease of electron density at its maximum (down to 60%) and a small increase of electron density in the topside ionosphere. These effects were registered in the morning and in the day-time 2–3 days before the earthquakes.

Direct measurements of plasma density and temperature over a zone of developing earthquakes also confirm the existence of seismic effects in the ionosphere. For example, a local trough in the ion density N_i of the order of 20% of its background value and an increase of ion temperature T_i were revealed from the AE-C satellite data above an earthquake center (Liperovsky *et al.*, 1992). The measurements were carried out at 150 km altitude about 14 h before the earthquake onset.

Similar results were obtained on the ISIS-2 satellite when measuring the parameters of electron density (N_e) in the ionosphere at altitudes ~1400 km (Liperovsky *et al.*, 1992). A local trough in the N_e distribution (15–20%) and a maximum in the electron temperature (T_e) distribution over the earthquake center 2 and 6 h before the main shocks were demonstrated. In both cases the ionospheric plasma disturbances had a characteristic spatial scale ~200–300 km.

Evidence for a connection of electromagnetic phenomena over a wide frequency range with earthquakes have been obtained by various authors (Gokhberg *et al.*, 1982; Parrot and Lefeuvre, 1985; Parrot and Mogilevsky, 1989; Chmyrev *et al.*, 1989; Larkina *et al.*, 1989; Bilichenko *et al.*, 1990; Fraser-Smith *et al.*, 1990; Mikhaylova *et al.*, 1991; Molchanov *et al.*, 1992, 1993; Serebryakova *et al.*, 1992; Hayakawa *et al.*, 1993, 1996; Parrot, 1994; Hayakawa and Fujinawa, 1994; Hayakawa, 1996). In these works the increased level of electromagnetic radiation connected with an enhancement of seismic activity was shown, based on both a statistical analysis of satellite data on ELF/VLF emissions over earthquake zones and on event studies for some specific earthquakes.

In particular, Serebryakova *et al.* (1992) performed an analysis of Cosmos-1809 satellite data on ELF emissions correlated with aftershocks of the Spitak earthquake (Armenia, December 1988). As a further development of this study, results are presented here of measurements of electron density N_e and its small-scale fluctuations dN_e from Cosmos-1809 for the same events which were analyzed in that article. These results also involve new data, both on ELF emissions and on ionospheric plasma density irregularities, over the earthquake region.

EXPERIMENTAL RESULTS

The Cosmos-1809 satellite was operating at altitudes ~950 km. ELF/VLF measurements were performed with a five-channel parallel-spectrum analyzer with central frequencies $f_0 = 140$, 450, 800, 4500 and 15 000 Hz, with the filter bandwidth $\Delta f = f_0/6$. The sensitivity for the electric component was $5 \cdot 10^{-7}\,\mathrm{V/m(Hz)}^{1/2}$, and for the magnetic component $10^{-5}\,\mathrm{nT/(Hz)}^{1/2}$ at frequencies ~1 kHz; the dynamic range was 60 dB.

To measure the ionospheric plasma density N_e and its fluctuations dN_e, a high-frequency capacitance impedance probe IZ-2 was used. N_e and dN_e were determined from the measurements of the probe capacitance variations depending on the ionosphere permittivity at a frequency $f = 5.025$ MHz. When the plasma density varies, the circuit capacitance is changed and, correspondingly, its resonant frequency is changed too. This method has both high sensitivity and time resolution. The time constant of the instrument determined by the HF-filter is 20 ms. For the data presented below, the maximum spatial resolution dependent on the telemetry sampling rate was approximately 20 km for the N_e measurements and about 4 km for the dN_e channel.

After the strong earthquake in Armenia on 7 December 1988, aftershocks of various intensities were registered near the epicenter for about three months. To study the ionospheric response to the aftershocks of this earthquake, 24 orbits of the Cosmos-1809 satellite in a longitudinal zone ±12° from the epicenter were selected. In this article we present the results for five satellite orbits closest to the earthquake center shortly before the shocks with energy class $E \geq 7$ (Christoskov *et al.*, 1983). Parameters of the aftershocks considered here are shown in Table 1 which presents the date and time (*UT*) of the shocks, the geographic latitude (φ) and longitude (λ) of epicenter, time difference (Δt) between the satellite crossing the epicenter latitude and the time of the shock; K_p denotes the 3 h index of planetary geomagnetic activity.

The parts of the satellite orbits where the anomalous radiation (see below) was observed are presented in Fig. 1 in geographic coordinates φ and λ. The asterisk marks the location of the epicenter, and the solid line corresponds to the L-shell of its projection at an altitude of 100 km ($L = 1.42$). In all the cases under consideration, except for the event of 31 January–1 February 1989 (see Table 1) the measurements of ELF emission intensity, ionospheric plasma density N_e and its fluctuations dN_e were made under conditions of only moderate geomagnetic activity.

Figure 2 represents the emission intensity for the magnetic component in the frequency channels $f_0 = 140$ and 450 Hz, the plasma density N_e and its variations dN_e over the Spitak seismic zone ~3.3 h before the shock on 20 January 1989 (see Table 1). The vertical arrow at 00.04.06 UT marks the moment when Cosmos-1809 crossed the geographic latitude of the earthquake center. The measurements were carried out in the night-time sector during a geomagnetic storm recovery phase with $K_p = 3_0$. As is seen from Fig. 2, the burst of intensity of electromagnetic radiation at frequencies ~140 Hz (bottom panel) with an amplitude up to 10 pT was observed in the longitude range $41.6° < \lambda < 42.0°$, i.e. approximately 2° to the west of the epicenter and in the latitude range $30° < \varphi < 33.1°$. A weaker increase of electromagnetic noise (up to 3 pT) was also observed in the channel $f_0 = 450$ Hz. At the higher frequencies, no increase of the noise level was registered. It should be noted that the radiation intensity in both channels (140 Hz and 450 Hz) is modulated with quasi-periods of 5–6 s.

It is seen from Fig. 2 that the maximum of the ELF radiation is located on the L-shell which corresponds to the projection of the epicenter at an altitude of 100 km ($L = 1.42$). The zone of increased intensity is shown in Fig. 2 by vertical dashed lines, and its dimension along the satellite orbit was ~450 km. In the same region, intense small-scale fluctuations of plasma density dN_e were observed (see upper panel of Fig. 2). Thus, it follows from Fig. 2 that plasma inhomogeneities with $dN_e/N_e \approx 6$–8%, with a characteristic spatial scale ~10 km along the orbit, are excited on the same magnetic field tube where anomalous seismic related ELF emissions have been observed (Serebryakova *et al.*, 1992).

Table 1.

No.	Date	UT	Δt (h)	φ (°)	λ (°)	E	K_p
1	20 January 1989	03.23.08	3.28	40.9	44.1	8.3	3_0
2	23 January 1989	23.47.34	0.17	40.9	43.9	9.0	3_0
3	26 January 1989	13.36.24	1.6	40.9	44.3	8.0	3_0
4	1 February 1989	00.18.44	1.7	40.9	44.0	7.2	6_0
5	8 February 1989	22.36.25	0.8	40.9	44.1	8.0	3_0

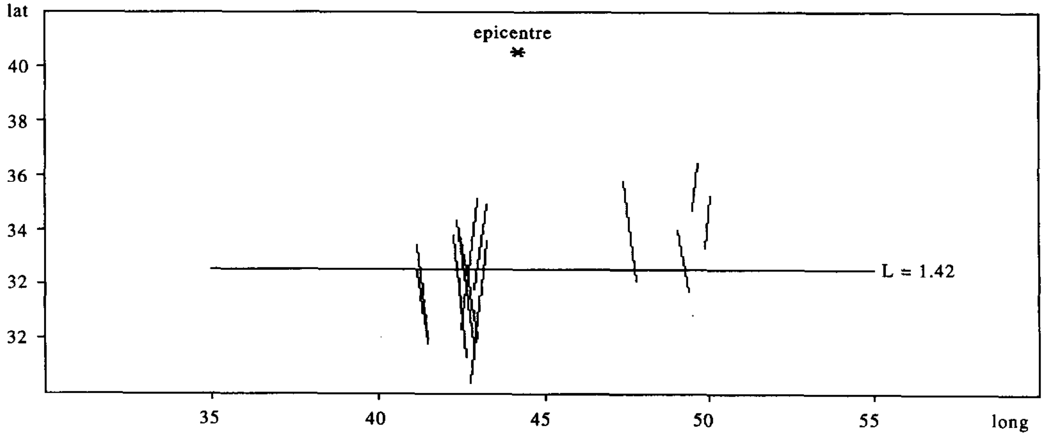

Fig. 1. Parts of the satellite orbits where the anomalous ELF radiation was observed.

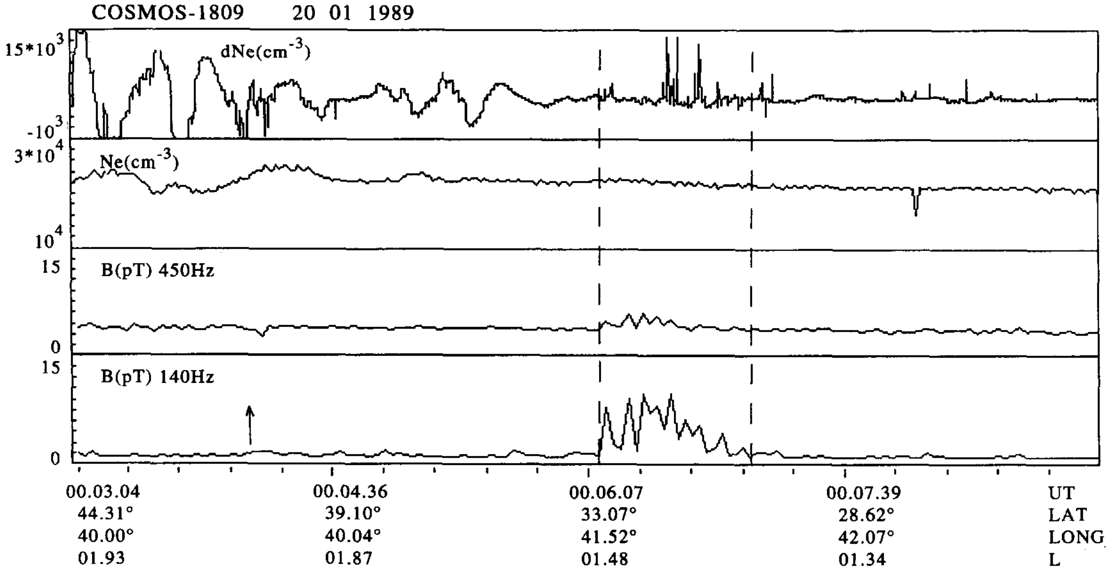

Fig. 2. ELF emission intensity for the magnetic component B in the frequency channels $f_0 = 140$ and 450 Hz, plasma density N_e and its variations dN_e over the Spitak seismic zone ~3.3 h before the shock on 20 January 1989.

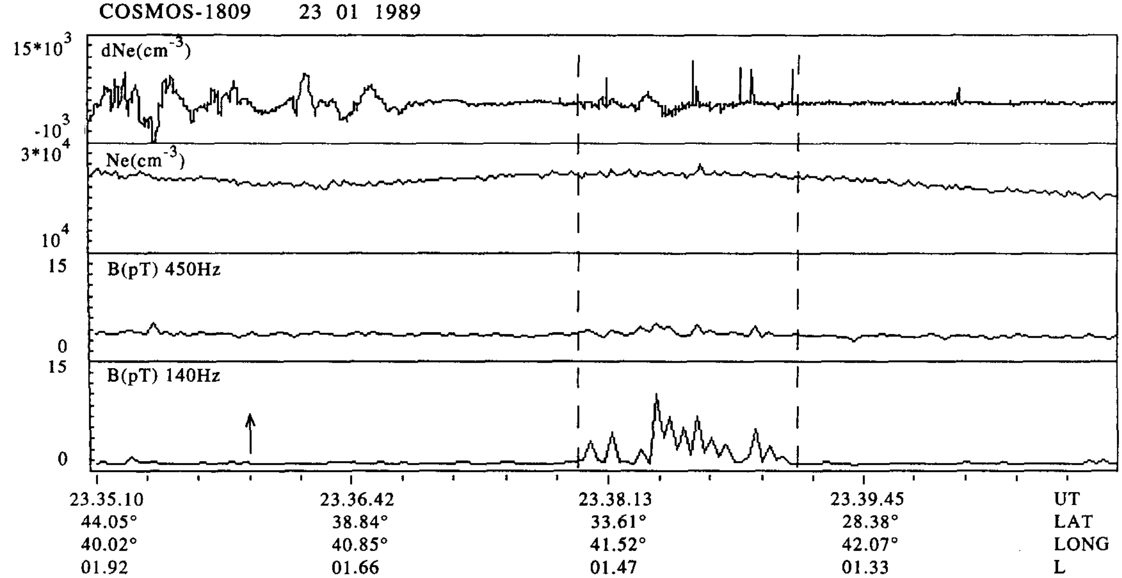

Fig. 3. The same as Fig. 2 but ~ 10 min before the shock on 23 January 1989.

Another example is presented in Fig. 3 (event 23, January 1989). Similarly to the case considered above, a burst of electromagnetic radiation at frequencies ~ 140 Hz was observed in the latitude zone ~ 4°, with the maximum within the geomagnetic flux tube of the earthquake region ($L \sim 1.4$). This event was registered, 1.5° west of the epicenter, 10 min before the aftershock. The moment when the satellite crossed the epicenter latitude is marked by a vertical arrow. Measurements were performed in the dark ionosphere under conditions of weak geomagnetic activity ($K_p = 3_0$). Similarly to the previous case, modulation of the intensity was observed with a period of 5–6 s. A weaker increase of the level of emission intensity, with approximately the same periods of modulation, was observed at frequencies ~450 Hz, and the disturbed zone shown in Fig. 3 by vertical dashed lines had a scale ~ 600 km. Variations of the ionospheric plasma parameters in this case were similar to those of the preceding case. Quasi-regular 5–6 s variations of N_e exceeding mean values by 4–5% and small-scale fluctuations $\mathrm{d}N_e/N_e$ with magnitudes of 1–8% were observed. This gives evidence for the presence of plasma density inhomogeneities with scales of 40–60 km and 4–10 km, respectively, at altitudes ~ 1000 km in the ionosphere over the earthquake zone. Large variations of N_e and plasma density fluctuations in both cases were also observed north of the Spitak zone. Their origin will be discussed below.

The characteristic feature of the next example (31 January–1 February 1989) is the absence of the quasi-periodic modulation of the emissions at frequencies 140 and 450 Hz. As is seen from Fig. 4, a wider range of inhomogeneity sizes (from 20 to 50 km) along the whole part of the satellite trajectory was observed in this event. This is apparently connected with the fact that in this case the measurements were carried out under conditions of high geomagnetic disturbance, $K_p = 6_0$. The character of the fast fluctuations $\mathrm{d}N_e$ was practically unchanged as compared to the cases considered above. The maximum amplitude of radiation in the frequency channel $f_0 = 140$ Hz reached 14 pT.

In contrast to these three preceding cases, in the subsequent example for the event of 26 January 1989 observations were performed on the ascending part of the satellite orbit under sunlit conditions (Fig. 5). This resulted in higher N_e values and in a more homogeneous structure of the N_e distribution along the orbit, although some isolated zones were observed with irregularities with scale 30–40 km including those in the seismic region marked in the figure by vertical bars. The region itself is narrower (~ 350 km). The maximum amplitude of the emission at frequencies ~ 140 Hz is 20 pT. Small-scale (4–10 km) fluctuations of plasma density are 3% of the background N_e values.

Similar characteristics of ELF emissions and plasma density fluctuations were also observed in the next event (08 February 1989) which is shown in Fig. 6.

In all the cases described above, except for that in Fig. 6, considerable values of plasma density dis-

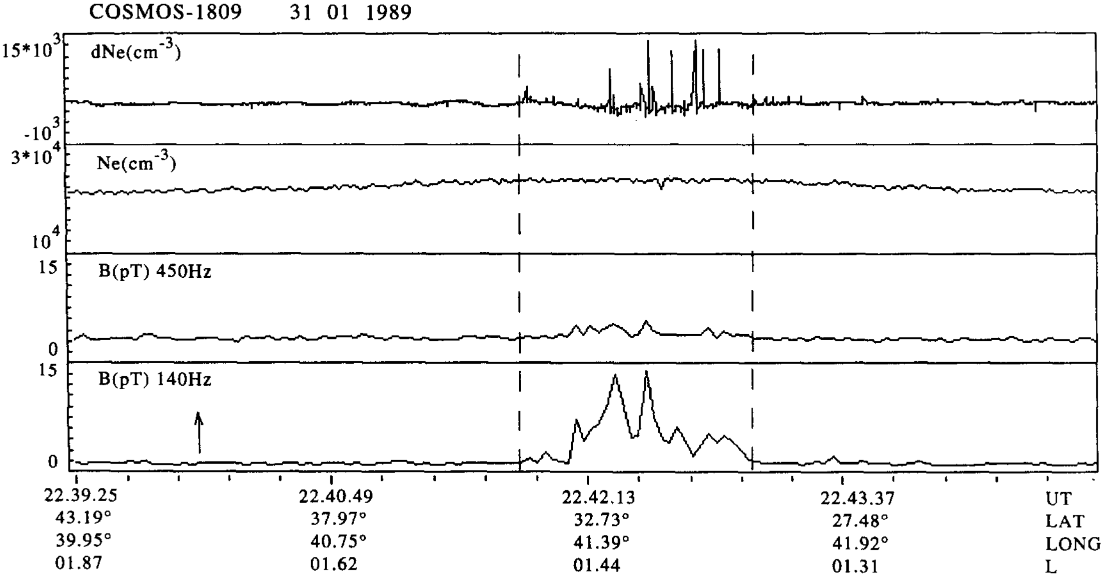

Fig. 4. The same as Fig. 2 but ~1.7 h before the shock on 31 January 1989.

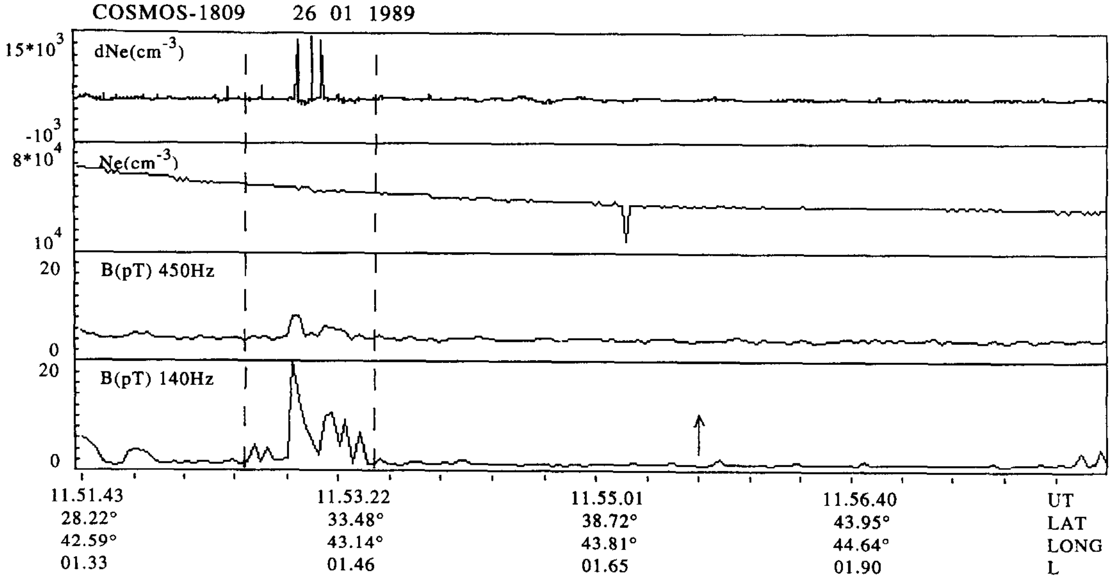

Fig. 5. The same as Fig. 2 but ~1.6 h before the shock on 26 January 1989.

turbances with characteristic spatial scales 50–200 km were registered to the north of the epicenter. The maximum values of the fluctuations dN_e (up to 20%) were observed on the equatorward wall of the main ionospheric trough (MIT) as is clearly seen from Fig. 7 in the latitude distribution of plasma density, both in the northern and southern hemispheres. Similar N_e fluctuations on the equatorward wall of the MIT are observed practically always (Gdalevich *et al.*, 1990), and ideas of the gradient-drift instability (Keskinen and Ossakow, 1983) here are applied to explain their generation.

DISCUSSION

Typical results for measurements of ELF emissions, plasma density and fluctuations of plasma density in the ionosphere over the zone of the Spitak earthquake

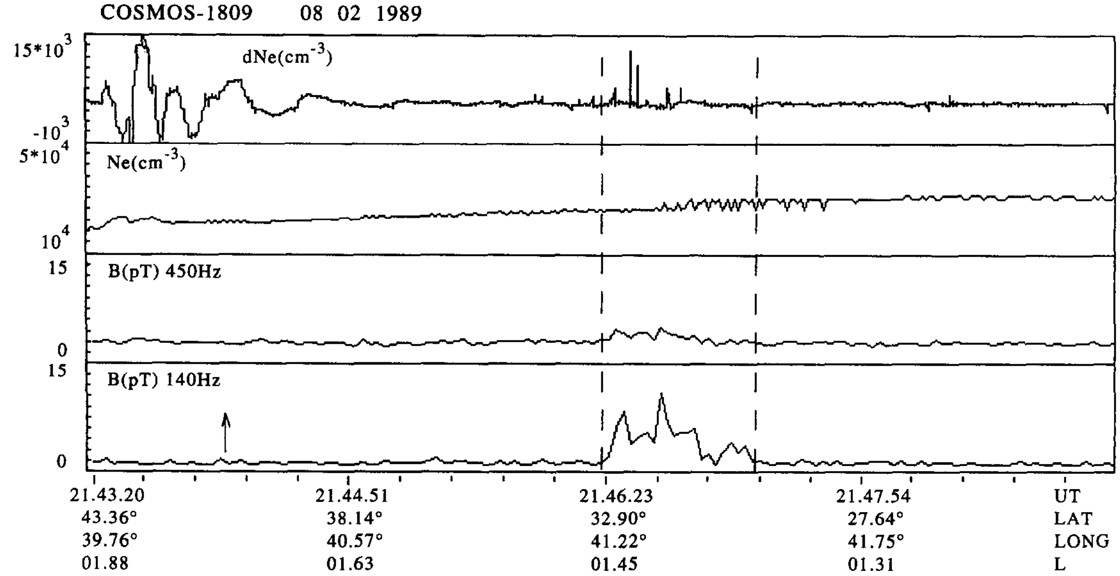

Fig. 6. The same as Fig. 2 but ~50 min before the shock on 8 February 1989.

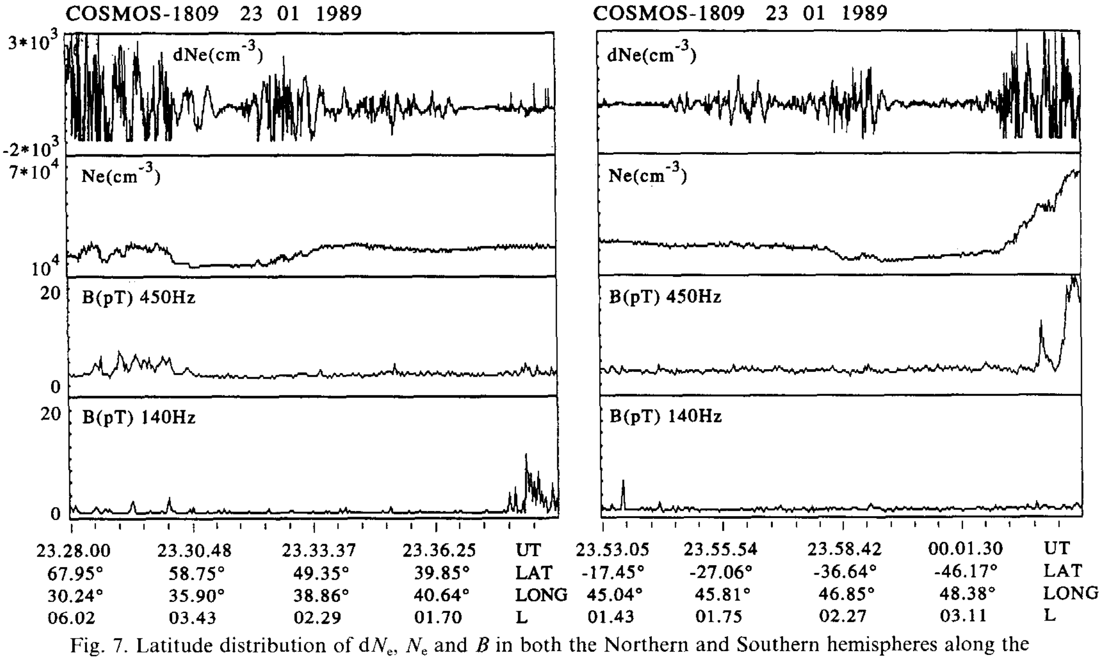

Fig. 7. Latitude distribution of dN_e, N_e and B in both the Northern and Southern hemispheres along the orbit which corresponds to Fig. 3.

during the period of its enhanced aftershock activity have been presented above. These results were obtained under different solar-geophysical conditions, i.e. for the sunlit and dark ionosphere, and for moderate and high levels of geomagnetic activity. It has been shown that emissions in the frequency range of 140–450 Hz are regularly observed within the *L*-shell whose foot is in the seismoactive zone. Such a result was first obtained by Serebryakova *et al.* (1992) on the basis of analyses of the first three events from Cosmos-1809 (Figs 2–4) and of data from the Aureol-3 satellite. In the present article this result is confirmed by two other events, shown in Figs 5 and 6 (bottom panels).

The new result of this study is that small-scale plasma irregularities $dN_e/N_e \sim 3$–8% with characteristic scales 4–10 km along the orbit have been revealed on geomagnetic field tubes connected to the epicentral region in which seismogenic ELF emissions were observed simultaneously.

Let us pay attention to the quasi-periodic ($T = 5$–6 s) oscillations in the ELF wave intensity first reported by Serebryakova *et al.* (1992), and also presented in the figures above. These oscillations occurring in the frequency range of pre-earthquake geomagnetic pulsations observed by Fraser-Smith *et al.* (1990), Molchanov *et al.* (1992), Hayakawa *et al.* (1996) and Hayakawa (1996) can be considered as an indication of the coupling of ULF and ELF wave processes during the precursor phases of earthquakes.

In contrast to the results of measurements made on board AE-C and ISIS-2 satellites (Liperovsky *et al.*, 1992), here we did not observe seismic related large-scale peculiarities in the distribution of plasma density and temperature measured by Cosmos-1809. This is probably connected with the fact that, despite the data presented here being related to the aftershocks of a strong earthquake, the energy class of the aftershocks themselves was $7.2 \leq E \leq 9$ which is typical of weak earthquakes. Moreover, the sequence of seismic events was so dense (up to several shocks per day) that, in this case, we could discuss only the effects connected with high seismic activity but not with the processes of earthquake development.

The increase of ELF emission intensity, at frequencies of 140–450 Hz on the magnetic field tube projecting onto the lower boundary of ionosphere above the earthquake region, seems to us to be connected with the seismic processes because, first, on the adjacent satellite orbits (approximately 22° to the west and east) similar increases in the emission level were not registered and, second, in this region the sources of anthropogenic (technological) low frequency effects on the ionosphere are absent. This observation agrees with the results of other satellite studies (Molchanov *et al.*, 1993; Parrot, 1994).

The main result of the present study is observation of small-scale plasma inhomogeneities dN_e with characteristic spatial scales 4–10 km in the ionosphere over the earthquake region. A physical model for such inhomogeneities is developed in the accompanying paper by Sorokin *et al.* (1996). According to that article, the dissipative instability of acoustic-gravity waves in the lower ionosphere leads to the generation of conductivity variations. These variations in the presence of a DC electric field result in the generation of shear Alfven waves which transfer electric field and related plasma disturbances from the E-layer to the upper ionosphere.

CONCLUSIONS

Analyses of Cosmos-1809 satellite data on ELF emissions show that electromagnetic waves at frequencies of 140–450 Hz were regularly observed in the ionosphere over a region of enhanced aftershock activity, independently of the geophysical conditions. Small-scale (4–10 km) fluctuations of plasma density, $dN_e/N_e \sim 3$–8%, correlated with an increase of seismic related ELF emission intensity, were recorded. The latitude range of the disturbed zones of plasma density dN_e and ELF waves is $\Delta\varphi = 3$–4.5°.

The dissipative instability of acoustic-gravity waves in the lower ionosphere is considered as a possible mechanism for the generation of small-scale ionospheric plasma irregularities connected with seismic processes in the Earth. This mechanism is developed in detail in an article by Sorokin *et al.* (1996).

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