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EFFECTS ON MIDLATITUDE IONOSPHERE OBSERVED FROM GROUND-BASED IONOSONDE DATA OBTAINED AT ALMA-ATA STATION DURING STRONG GEOMAGNETIC STORMS

The ionospheric effects of fourteen great geomagnetic storms occurred in the 1986-2005 time period observed over Alma-Ata (43.25_N, 76.92_E) were studied experimentally using ground-based ionosonde. The observations showed a number of unusual (for the Alma-Ata location) ionospheric phenomena during the active phase of the geomagnetic storms, along with a negative phase in the ionospheric F2-layer disturbance an anomalous formation of the E, E2, and F1 layers at nighttime, and the appearance of aurora-type sporadic E layers were found. Processes of interaction of energetic neutrals with the upper atmosphere modeled by Bauske et al. (1997) for magnetically disturbed conditions seem to explain the phenomena of ionization of F1 and E regions at night.

INTRODUCTION

Numerous papers devoted to the investigation of the F2-layer response to a geomagnetic storm, information about progress in understanding this event is given in a recent review by Danilov (2005) and references therein. Summarizing the thermospheric reaction to geomagnetic disturbances, the author concludes that a large amount of energy deposited into the thermosphere at high latitudes during such geomagnetic disturbances leads to an increase of the neutral gas temperature T and variations of the neutral composition (depletion of the atom-to-molecules ratio, [O] / [N_2]). These both factors are a main reason for the decrease in electron concentration NmF2 (the negative phase of an ionospheric storm) in the high-latitude ionosphere. A circulation which is directed equatorward spreads the heated gas to lower latitudes. The conflict between the storm-induced and regular circulations determines the spatial distribution of the negative and/or positive phases in various seasons. In the frame of this summary, we would like to stress that reaction of the ionosphere can be different during similar geomagnetic storms and depending on season.

As for the E-region, geomagnetic storm effects are most widely-studied at high latitudes, though it's known that during magnetic storms an anomalous increase in the ionization density of the nighttime E-region is observed at low and middle latitudes. Very clear examples of the unusual behavior in the low and middle latitude ionosphere were observed in the Brazilian and Kazakhstan sectors during 13 March 1989 [Batista et al., 1991], 30-31 October 2003 and 20-21 November 2003 geomagnetic storm periods [Gordienko, 1997; Gordienko et al., 2005]. The ionograms over Cachoeira Paulista (22.5^{0}S, 45^{0}W) and Alma-Ata (43.25^{0}N, 75.92^{0}E) showed an auroral type sporadic E and night E layers during the magnetically disturbed periods. The presence of the F1 layer at night was observed on the Fortaleza (4^{0}S, 38^{0}W) and Alma-Ata ionograms, a phenomenon that has never been observed over the stations at nighttime under quiet geomagnetic field.

Lyons and Richmond [1978] and Tinsley [1979] assumed that a possible cause of these density enhancements is the precipitation of energetic neutral atoms with energies of 1–100 keV from the ring current zone during a magnetic storm, when a considerable amount of energy comes into the ring current from the inner magnetosphere. These energetic neutral particles are formed as a result of a charge-exchange interaction of the ring current ions with neutral hydrogen of the geocorona. As a result of the interaction, a cold proton and an energetic neutral are formed. The magnetic field does not influence the trajectory of motion of energetic neutrals, and the latter are able to leave the ring current zone. Particles moving earthward enter the dense atmosphere and interact with gas particles during elastic and nonelastic collisions. During each of these collisions, these particles lose part of their energy, which is spent on ionization. Complicated processes of interaction between energetic neutrals precipitating from the ring current zone and neutral particles at altitudes of the lower ionosphere were modeled by Bauske et al. [1997]. The authors evaluated the significance of the ionization production by precipitated neutralized ring current particles using a combination of a ring current decay model and an ionosphere model. To run the simulation, the AMPTE satellite measurements recorded during the magnetic storms on 20/21 April 1985 (moderate magnetic activity; -89 nT i Dsti-127 nT) and 9 February 1986 (more severely disturbed conditions; -202 nT i Dst i -286 nT) were used. The ionosphere simulation was performed for a location near Arecibo at 30^{0} magnetic latitude (L = 1.33) and for conditions on the days of the ring current measurements. It was found that the production rate maximized in an extended region between 25^{0}and 50^{0} magnetic latitudes and in an altitude range between 115 and 135 km. What is important is that the simulation reproduced the storm-induced enhancements of the ionization density in the night E- and F1-regions, which at 180 km altitude reaches a factor of more than five, and shows a good qualitative agreement with the Alma-Ata observations. Within this general frame work we decided to perform a statistical study of the anomalous increase in the ionization density of the night E- and F1-regions using the Alma-Ata ionospheric data available for fourteen intense geomagnetic storms (Dst Ә-190 nT) observed at the Alma-Ata station in the period of 1989-2005 to control the geomagnetic storm effects in the regions and estimate the anomalous ionization at night.

DATA

The hourly and 1-min values of the critical frequency foF2, a measure of the peak electron density in the F2-layer (N=1.24f^{2} ө 10^{10} m^{-3}, where f is in MHz), obtained at the Alma-Ata station [43.25N, 76.92E] during quite/storm time intervals are used to study the F2-layer responses to the great geomagnetic storms. The foF2 data are obtained by semi-automatic ionogram scaling with a program made in the Institute of Ionosphere, the source of the ionogram is the digital ionosonde PARUS. A description of the ionosonde PARUS is available at the Web site http://www.izmiran.rssi.ru. The hourly values of the fluctuating component of the critical frequency (DfoF2) obtained as a relative deviation of the hourly foF2 values from their corresponding background level are used to estimate intensity of the ionosphere disturbances:

$$DfoF2 = [(foF2-foF2_{med})/foF2_{med}]$$

(in % according to foF2med);

The background level *(foF2med)* used in the study is the 13-day running average computed for each hour with the averaging interval L=13 days. Using 1-min values of the critical frequency foF2, the local time effects in the nighttime ionosphere are analyzed in details to study anomalies in the ionization density of the lower ionosphere during magnetically disturbed nights. The International Reference Ionosphere (IRI) model is used to estimate electron density in the night ionosphere for quiet conditions in the corresponding epochs. The Dst indices were downloaded from ftp://ftp.ngdc.noaa.gov/STP/ to obtain information about the planetary geomagnetic activity.

RESULTS

The list of the geomagnetic storms analyzed in the paper to study the disturbance scenario for the ionosphere observed at Alma-Ata station is given in

Table 1

#	Date dd.mm.yy	UT hh:mm	χ^0 / Δt, hr	Geomagnetic and IMF activity			Nighttime E-layer characteristics					Nighttime F1-layer characteristics				Descript. index
				Dst/Bz/SI nT	K p	$^{-1}$	Date dd.mm	LT hh:mm	foE MHz	$\times 10^4$ $^{-3}$		Date dd.mm	LT hh:mm	foF1 MHz	NmF1 $\times 10^4$ el.s^{-3}	
										obs.	IRI					
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	06.02.86	13:12	100 / 3	-300/-/-	8 - 9	-	08.02	03:00	1.5	2.8	0.18	-	-	-	-	F, H, N, Es
2	13.03.89	01:30	85 / 10	-500/-/-	8 - 9	-	14.03	01:00- 02:30	1.7-1.8	3.6-4.0	0.40	-	-	-	-	F, H, N, Es
3	20.10.89	09:17	56 / -	-275/-/-	8	-	21.10	19:30- 20:15, 23:00	1.5	2.8	041					Es, H
4	17.11.89	09:26	70 / 8	-275/-/-	8	-	17.11 18.11	18:15- 23:45 00:45- 01:15	1.3-1.6	2.1-3.2	0.41	-	-	-	-	Es, H
5	09.04.90	08:45	40 / 10	-290/-/-	8	-	11.04	03:30	K	-	0.40	11.04	03:30	3.0	11.2	F, B
6	24.03.91	03:40	60 / 14	-300/-/-	9	-	25.03	01:15- 04:15	1.3-1.4	2.1-2.4	0.39	25.03	02:15	1.8	4.0	B, Es, H
7	09.05.92	19:59	120 / ≤ 1	-300/-/-	8 - 9	-	10.05	01:30	K	-	0.31	-	-	-	-	E, N, Es
8	31.03.01	00:54	90 / -	-380/-46/73	8 - 9	830	01.04	02:30- 03:30	1.7	3.6	0.32	-	-	-	-	F, H, K
9	29.10.03	03:30	70 / 7	-400/-30/140	9	>800	31.10	01:50- 05:30	1.2-1.3	1.8-2.1	0.24	31.10	01:50- 05:30	1.65	3.4	Es, H, K, N, V, F
10	20.11.03	08:04	60 / 7	-450/-60/60	8 - 9	>800	20-21.11	22:00- 05:00	1.7-2.2	3.6-6.0	0.24	20.11	21:00	2.4	7.1	H, F, K, Es
11	26.07.04	22:28	100 / ≤ 1	-190/-25/95	8 - 9	1050	27.07	04:23 23:50	1.7 1.6	3.6 3.2	0.95 0.20	-	-	-	-	H, F, S, Es, K
12	07.11.04	18:31	157 / -	-375/-30/41	8 - 9	700	No data for November 4÷7; H, A, F, N, K on November 8-11									
13	15.05.05	02:38	60 / 4	-250/-43/67	8 - 9	900	A, K, H, F on May 15-20									
14	24.08.05	08:12	/3	-225/-55/-	8-9	800	25.08	03:45	1.5	2.79	0.17					Es, N, E2, F

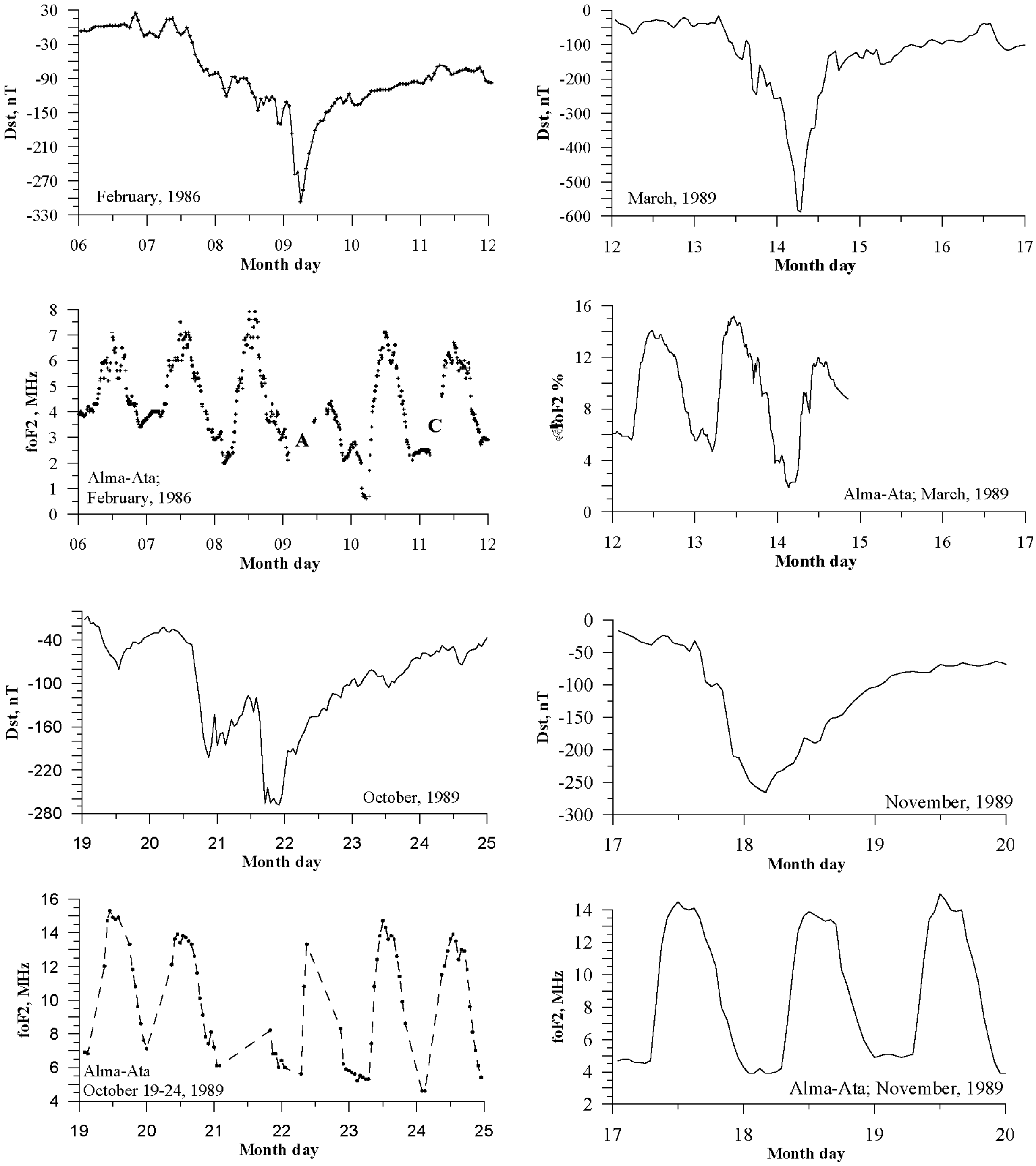


Figure 1. The critical frequency of the F2 layer (foF2) for different events of geomagnetic storms

Table 1, where dates, time (Universal Time (UT), Local Time (LT), the sun zenith angle (c)), geomagnetic activity (Dst, Bz, SI, Kp) and solar wind speed (V) are given for more information. Also, the Table presents information about the time delay for the ionosphere responses to the geomagnetic storms (Dt) and the nighttime E- and F1-layers characteristics. In addition to the information, many unusual phenomena found on the ionograms for the time period are pointed in the Table: spread echoes (F), sporadic layers (Es), completely blanketing of higher layers by sporadic Es layers (A), reflections from irregular ionosphere (abnormal stratification and satellite traces (H), forked traces (V), oblique moving echoes (N) preventing unambiguous interpretation), z mode (Z), night E-layer seen by retardation in the

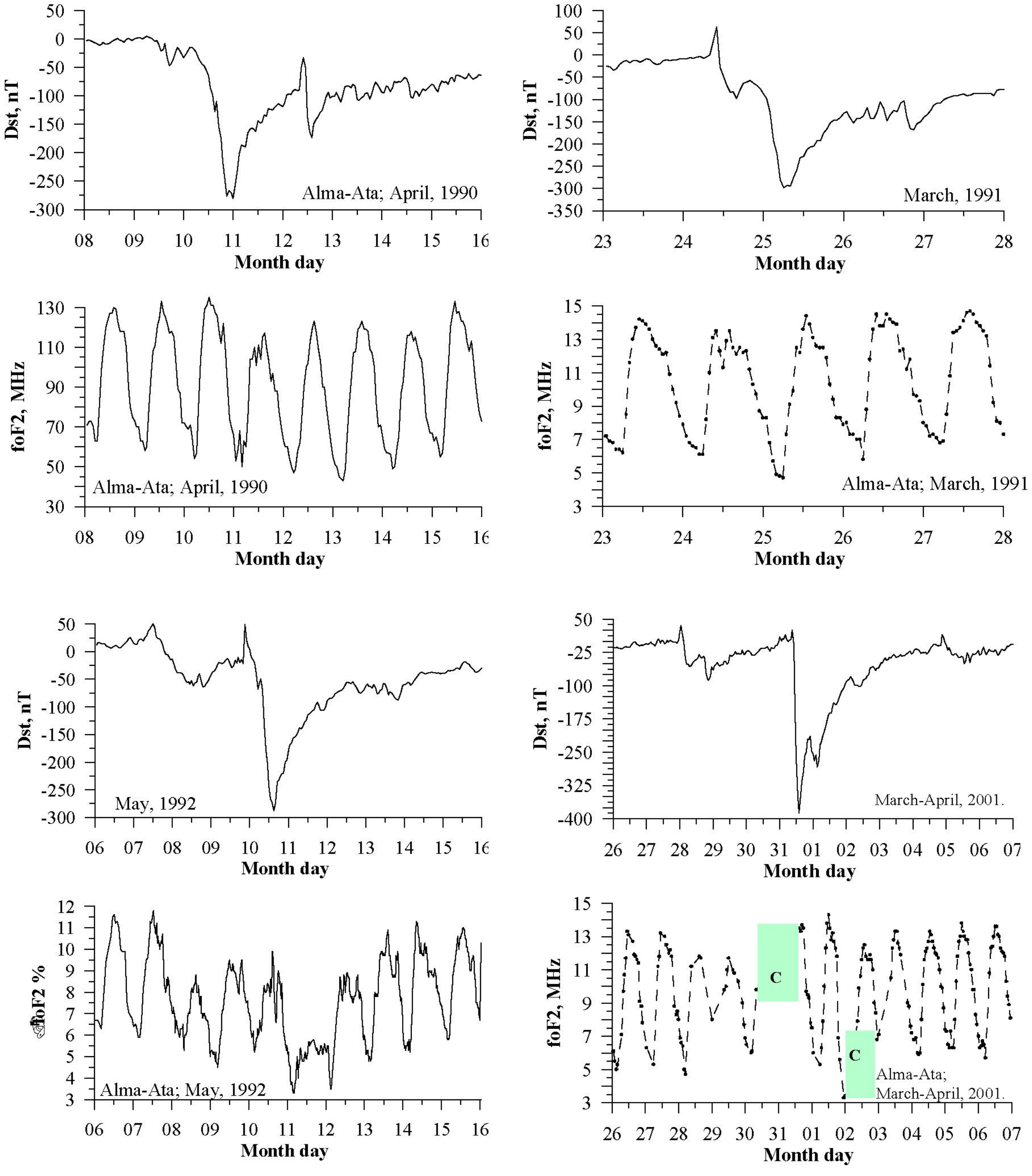


Figure 1. (continuation)

low frequency end of the F traces (K). Often, superpositions of the phenomena influence the measurement so that the measurements are beyond any interpretation.

Figure 1 shows examples of the critical frequency of the F2 layer (foF2) during several sequent days, including quiet and disturbed geomagnetic conditions, for each of the geomagnetic disturbances considered. The plots show that decrease in the electron density NmF2 (the negative ionosphereic storms) that occurred on the period of maximum disturbances in the geomagnetic field is a main feature in the ionosphere disturbances. It was found that if the geomagnetic storm appears in morning or daytime (7hr Ə t < 20 hr), the ionospheric storm is observed about 4ё14 hrs after sudden commencement of the geomagnetic storm; if the geomagnetic storm appears in evening or nighttime (7час>ti20час), the ionospheric storm is observed practically right away, DtƏ1hr (see column 4 in Table 1).

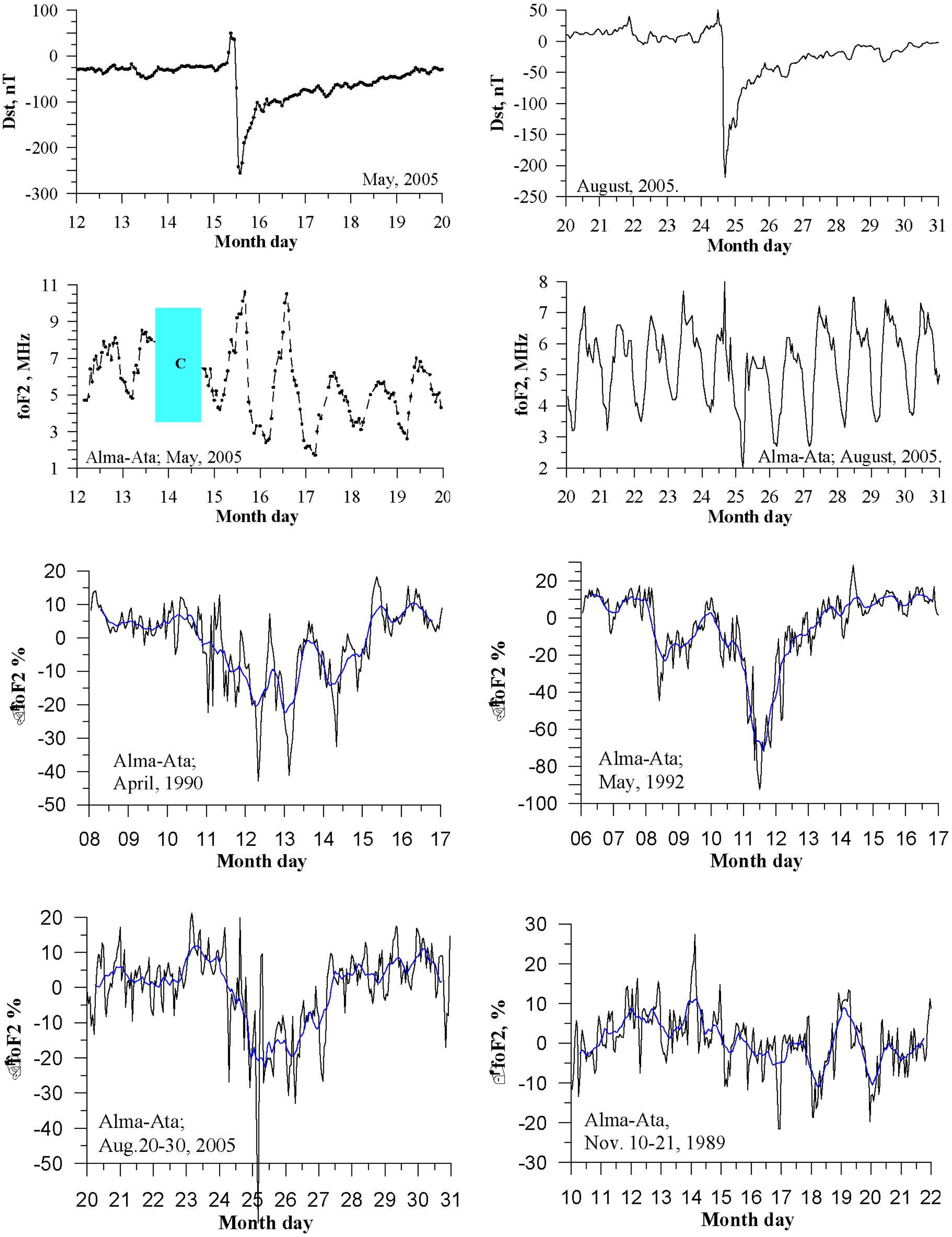


Figure 2. The fluctuating component of the critical frequency (DfoF2)

Intensity of the ionospheric storms run up to 40% and more, some examples are given in Figure 2. The largest depression in NmF2 (through foF2) is observed about 18ё24 hrs after the largest decrease in geomagnetic Dst variation. Also, Figures 1 and 2 show that the reaction of the ionosphere can be different during similar geomagnetic storms and depending on season. Thereupon, we would like to draw reader's attention on a fact that under the equal characteristics and conditions for beginning of the

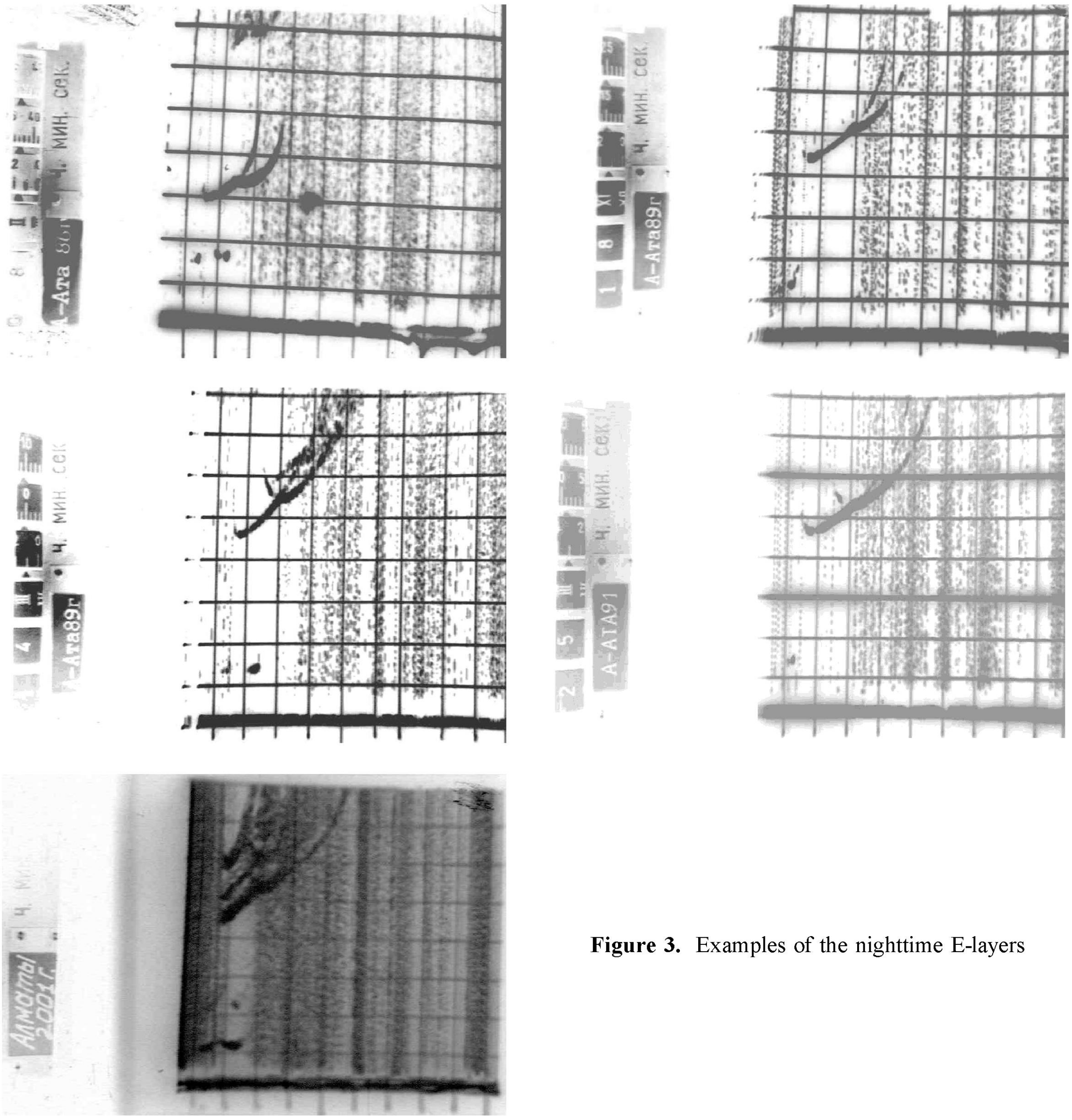


Figure 3. Examples of the nighttime E-layers

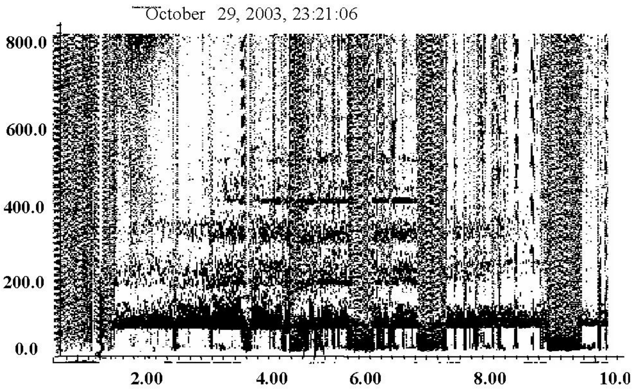
geomagnetic storms the degree of ionosphere disturbance is not always correlate with the degree of geomagnetic field disturbance that, may be, can happen because of distortion of the ionosphere response by additional ionosphere disturbances of other origin (for example meteorological origin), an example is shown in Fig. 2 (two lower panels).

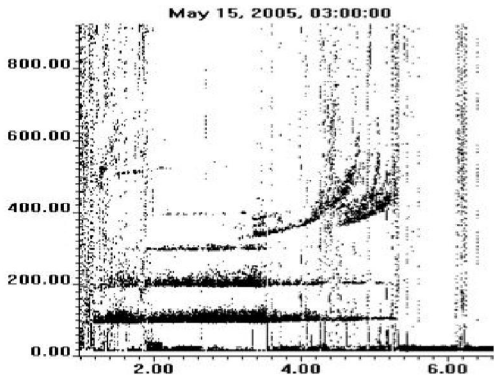
Examples of such unusual (for Alma-Ata location) ionospheric phenomena as the nighttime E-layer and aurora type Es appearance that were observed by ionosonde during the active phase of the geomagnetic storms are give in Figure 3 and Figure 4. The electron density in the nighttime lower ionosphere for quiet conditions on these epochs estimated by employing the International Reference Ionosphere 2001 (IRI-2001) is shown in Figure 5 by asterisks. Figure 5 shows that there is a very significant storm induced increase of the ionization density in the 110 to 200 km altitude range, which at 110km altitude reaches a factor of about 10.

CONCLUSION

The ionospheric effects of fourteen great geomagnetic storms (Dst Ə-150 nT) occurred in the 1986-2005 time period observed over Alma-Ata (43.25_N, 76.92_E) were studied experimentally using ground-based ionosonde PARUS. It was found that:

- if the geomagnetic storm appears in morning or daytime (7hr Ə t < 20 hr), the ionospheric storm is observed about 4ё14 hrs after sudden commencement of the geomagnetic storm; if the geomagnetic storm appears in evening or nighttime (7час>ti20час), the





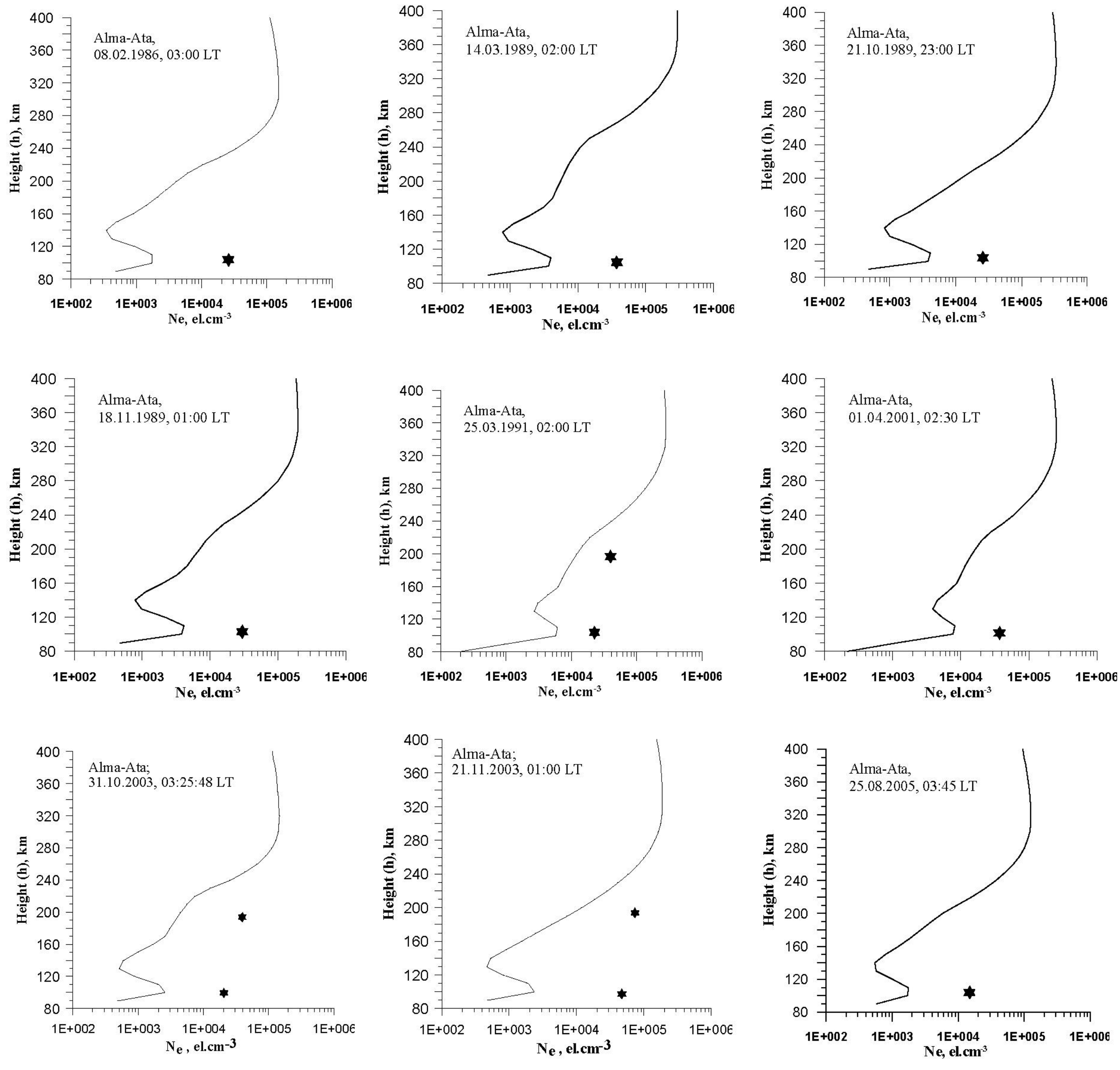


Figure 5. The N(h)-profiles in the nighttime ionosphere for quiet conditions on the epochs of the geomagnetic storms estimated by employing the IRI-2002. Asterisks show the storm induced increase in the ionization density in the 110 to 200 km altitude range

ionospheric storm is observed practically right away, DtӘ1hr;

- the largest depression in NmF2 (through foF2) is observed about 18ё24 hrs after the largest decrease in geomagnetic Dst variation;

- the degree of ionosphere disturbance is not always correlate with the degree of geomagnetic field disturbance, during similar geomagnetic storms reaction of the ionosphere can be different and depending on season;

- the nighttime E-, F1-layers and aurora type Es are observed by ionosonde during the active phase of the geomagnetic storms, applying the International Reference Ionosphere 2001 (IRI-2001) to estimate the electron density in the nighttime lower ionosphere for quiet conditions on these epochs shows that there is a very significant storm induced increase of the ionization density in the 110 to 200 km altitude range, which at 110km altitude reaches a factor of about 10 (Figure 5);

- many unusual phenomena are observed on the ionograms for the time period of the geomagnetic storms: spread echoes (F), sporadic layers (Es), completely blanketing of higher layers by sporadic Es layers (A), reflections from irregular ionosphere (abnormal stratification and satellite traces (H), forked traces (V), oblique moving echoes (N) preventing unambiguous interpretation), z mode (Z), night E-layer seen by retardation in the low frequency end of the F traces (K).

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Резюме

1986–2005 жж. мерзімінде өткен 14 қарқынды (Dst Ә 190 nT) геомагниттік дауылдар кезінде жүргізілген ионосфераның ионозондтық бақылау нәтижелері ұсынылған. F2 (foF2) қабатының критикалық мәліметтері бойынша бұл дауылдарға қатысты ионосфераның өзгеру морфологиясы зерттелген. Түнгі уақытта бақыланған геомагниттік дауылдардың басты фазасы мерзімінде ионосфераның мынадай ауытқу ерекшеліктері табылған: 1) түнгі уақытта Е және F1 қабаттарының пайда болуы, 2) 110 шақырым биіктікте Es авроральді типтегі экрандаушы спорадикалық қабаттың пайда болуы. Табылған ерекшеліктермен қатар ионосферада зондтаушы сигналдардың көлбеу және орын алмастыратын бейнелерінің қосымша стратификациялары пайда болады. Геомагниттік дауылдар кезіндегі ионосфералық ұйытқулардың негізгі сипаттамалары термосфералық айналымдар жүйесінің индуцияланған дауылы және термосфераның газды құрамының өзгеруі салдарынан болатын эффектілердің аясында қарастырылады. Ионосферадағы ауытқу құбылыстары төменгі ионосфераның биіктіктеріндегі бейтарап бөлшектері бар сақиналы ток аймағынан бөлініп шығатын бейтарап бөлшектердің өзара әрекетінің моделі шеңберінде талқыланады (Bauske et al., *Ann. Geophysicae 15*, 300-305, 1997).

Резюме

Представлены результаты ионозондовых наблюдений ионосферы во время 14 интенсивных (Dst Ә 190 nT) геомагнитных бурь в 1986–2005 гг. По данным критических частот слоя F2 (foF2) исследована морфология ионосферного отклика на эти бури. Обнаружены аномальные (для координат ст. «Алма-Ата») особенности ионосферы, в ночное время в период главной фазы геомагнитных бурь: 1) появление E и F1 слоев в ночное время; 2) возникновение экранирующего спорадического слоя Es аврорального типа на высоте порядка 110 км. Эти особенности сопровождались появлением дополнительных стратификаций в ионосфере, наклонных и перемещающихся отражений зондирующих сигналов. Основные характеристики ионосферных возмущений во время геомагнитных бурь рассматриваются в плане ожидаемых эффектов, происходящих в результате индуцированной бурей системы термосферной циркуляции и изменения газового состава термосферы. Аномальные явления в ионосфере обсуждаются в рамках модели взаимодействия энергичных нейтральных частиц, высыпающихся из зоны кольцевого тока, с нейтральными частицами на высотах нижней ионосферы (*Bauske et al. //* Ann. Geophysicae 15, 300-305, 1997).

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