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# Initial phase of mid-latitude aurora during strong geomagnetic storms

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## Abstract

Analysing the initial mid-latitude aurora phase during strong geomagnetic storms we found that the initial phase of the mid-latitude aurorae observed at 630 nm emission during the strong geomagnetic storms on March 24, 1991, April 6, 2000, October 30 and November 20, 2003 is characterized by a short ( $\sim 1$  h) wave-like disturbance. This disturbance corresponds to the beginning of main phase of the magnetic storms. The marked effect of the mid-latitude aurorae is analyzed using data on magnetosphere and ionosphere conditions in observation periods. The features of the dynamics of the 630 nm emission intensity and its connection with the dynamics of magnetospheric–ionospheric structures are considered. Possible excitation mechanisms of the atomic oxygen emission (630 nm) during these disturbances are discussed.

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## 1. Introduction

Upper atmosphere emissions observed in the middle latitudes under undisturbed conditions are usually referred to as “airglow”. So-called “mid-latitude aurorae” (MLA) can be observed during strong geomagnetic storms in the middle latitudes. Physical processes and sources that form airglow and mid-latitude aurora are different (Chamberlain, 1961). The airglow refers to the photochemical excitation, while the aurora refers to the impact excitation.

The 630 nm emission is the dominating emission in both the airglow and MLA. During geomagnetic storms, the 630 nm emission intensity can essentially increase and exceed that in the airglow. In this case MLA is a dominating phenomenon in comparison with the airglow in the 630 nm emissions. Some MLA forms are within the plasmopause area (Rassoul et al., 1993), and can be

employed to diagnose the motion of the plasmopause and the auroral oval during geomagnetic disturbances. However, there is a problem of the separation of the airglow and the initial MLA phase (Chamberlain, 1961), when 630 nm emission intensities resulted from photochemical and impact excitations are still comparable.

In this paper, we focus on observations of the mid-latitude aurorae taken place during extreme magnetic storms in the Asian region near Lake Baikal. Our purpose here is to reveal peculiarities of 630 nm emission variations at the initial MLA phase and their relations with the dynamics of the magnetosphere and ionosphere structures.

## 2. Instruments and data

In our study, we use results of the airglow observations performed at the Geophysical observatory of ISTP RAS SB (52°N, 103°E) for 1989–1993 and 1997–2004. MLA events during four extreme storms (March 24, 1991, April 6, 2000, October 30 and November 20, 2003) are considered. Airglow and MLA data were obtained by zenith pho-

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tometers with tilting filters ([OI] 557.7 and 630 nm,  $\Delta\lambda_{1/2} = 1\text{--}2$  nm). Besides 557.7 and 630 nm emissions, emissions were registered in the near-infrared region (720–830 nm) and in the ultraviolet (360–410 nm). Angular viewing fields of the photometer channel were 4–5°. Absolute calibration of the equipment measurement channels was conducted at some periods from reference stars and then was checked using reference light sources. To determine magnetosphere conditions, we employed AE and Dst data from the World Data Centre (<http://swdcdh.kugi.kyoto-u.ac.jp>) in Kyoto; NASA data on the solar-terrestrial physics from ([http://cdaweb.gsfc.nasa.gov/cdaweb/istp\\_public](http://cdaweb.gsfc.nasa.gov/cdaweb/istp_public)). Positions of the equatorial boundary of the statistical auroral oval were obtained from data of NOAA POES (<http://sec.noaa.gov/pmap/pmapN.html>) and DMSP ([http://sd-www.jhuapl.edu/Aurora/ovation/ovation\\_display.html](http://sd-www.jhuapl.edu/Aurora/ovation/ovation_display.html)).

### 3. Observations and results

Fig. 1 presents the behavior of the [OI] 630 nm atomic oxygen dominating emission during the four extreme magnetic storms (curves 1): March 24, 1991 (a), April 6, 2000 (b), October 30 (c) and November 20, 2003 (d). Curves 2

are typical night variation of the 630 nm emission that results from the airglow.

From Fig. 1 we can single out a time interval of transition from the night airglow to the mid-latitude aurora that is characterized by 630 nm emission intensity fluctuations with amplitudes exceeding those of preceding airglow variations. This interval for two magnetic storms (March 24, 1991 and April 6, 2000) is shown in more detail in Fig. 2. Curves in this figure were obtained with removing low-frequency trends (2- and 3-degree polynomials, respectively).

Vertical dashed lines in Fig. 2 show part time intervals, which can be assigned to the airglow and MLA. The interval between the airglow and MLA determined with confidence is conventionally denoted “WD”, since emission variations at this period are akin to wave disturbance (WD). Variations in 630 nm emission intensity with amplitudes about 20–40 R and periods of 1–1.5 h a most probably caused by the acoustic-gravity waves (AGW). A drastic increase of the emission intensity up to 40–80 R is typical of the WD interval. Note that the rate of the 630 nm emission increase ( $\Delta J_{630}/\Delta t$ ) in the WD interval is practically identical to the following increase of this emission in MLA. This peculiarity (WD) may be interpreted as both

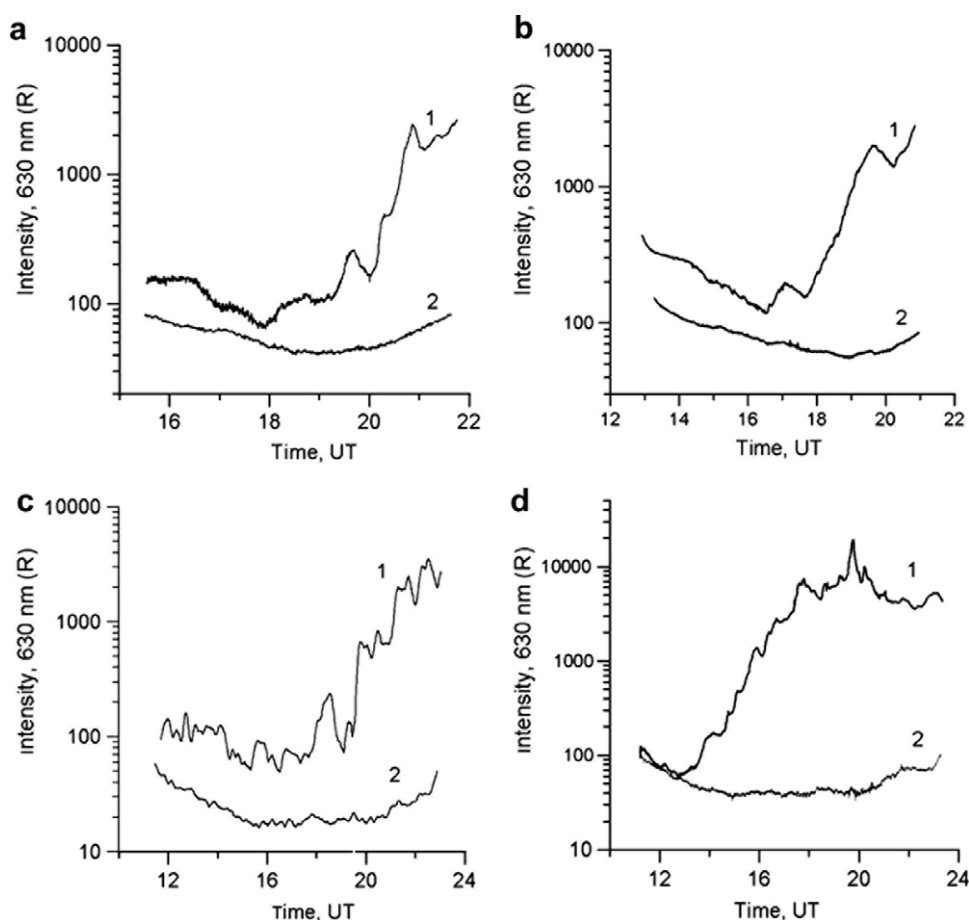


Fig. 1. Time variations of 630 nm emission intensities during the magnetic storms on March 24, 1991 (a), April 6, 2000 (b), October 30, 2003 (c) and November 20, 2003 (d) according to the ISTP SB RAS Geophysical observatory observations (curves 1). Curves 2 are typical night variations of the 630 nm emission that results from the airglow.

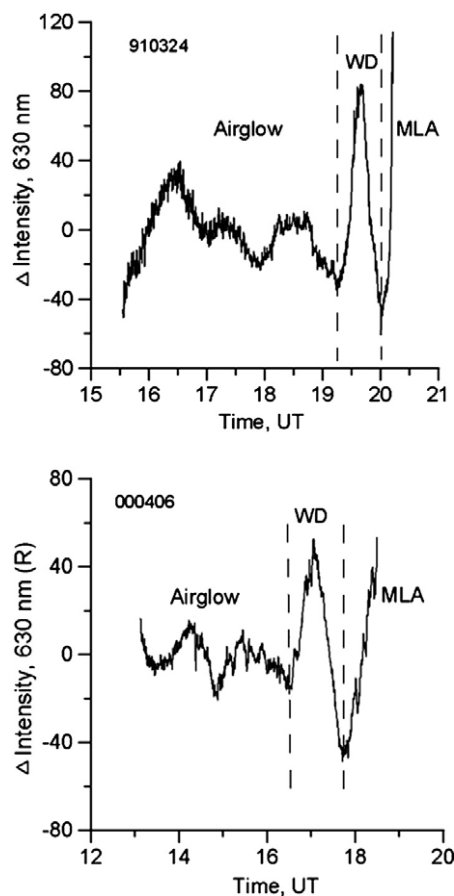


Fig. 2. Time variations of 630 nm emission intensities during the magnetic storms on March 24, 1991 and April 6, 2000 after removal of trends (2- and 3-degree polynomials, respectively).

the AGW amplitude “amplification” and the beginning of MLA. The nature of this wave disturbance is of interest in both cases. We assume that the WD interval corresponds to the initial MLA phase. Based on this assumption we consider the specific MLA cases below.

Table 1 lists key features of the 630 nm emission at the initial MLA phase (WD interval) and the parameters of corresponding magnetic storms. A common feature of the initial MLA phase, as could be determined from hour values of Dst index, is MLA occurrence at the beginning of the main geomagnetic storm phase despite a great difference in dynamic characteristics of the storms considered.

It is obvious from Table 1 that for all the cases the initial MLA phase is registered in different geomagnetic activities and at different local time. In three cases, this phase corresponds to the period of the considerable geomagnetic activity (high Dst index); and in one case (April 6, 2000) to a small negative value of Dst index. This implies that the position dynamics of main magnetospheric structures at the initial MLA phase during the effect under study can be different.

### 3.1. April 2000 event

Fig. 3 demonstrates the geomagnetic situation for the period of the WD in the 630 nm emission on April 6, 2000. In this figure, vertical dashed lines indicate the beginning and end of the WD interval as well as the 630 nm emission intensity maximum in this interval. The MLA commencement in the 630 nm emission was registered at a relatively quiet geomagnetic period of 23.23–23.33 LT

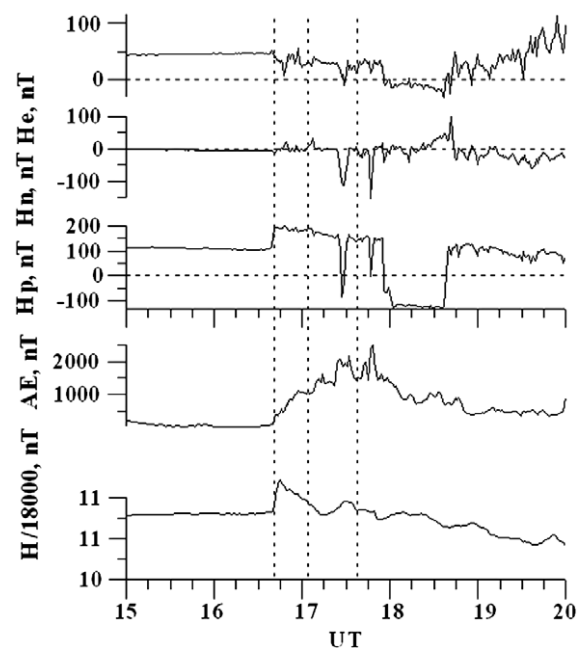


Fig. 3. Variations of geomagnetic field according to the measurements at the geostationary orbit (GOES-10  $\lambda = 225^\circ\text{E}$ , upper panel), in the auroral zone (AE-index) and at the ground level in Irkutsk (lower panel) for the initial mid-latitude aurora phase on April 6, 2000.

Table 1  
Principal parameters of the observed effect within the initial phase of MLA as well as parameters of respective MSs

	March 24, 1991	April 6, 2000	October 30, 2003	November 20, 2003
Dst <sub>min</sub> (nT)	−281	−287	−401	−472
Beginning of main phase of MS	16 UT	17 UT	18 UT	09 UT
Beginning of MLA ( $J_{630}$ )	~19.14 UT (02.06 LT)	16.31 UT (23.23 LT)	17.45 UT (00.37 LT)	13.12 UT (20.04 LT)
Time of decrease of $J_{630}$	19.41 UT (02.33 LT)	17.04 UT (23.56 LT)	18.32 UT (01.24 LT)	14.11 UT (21.03 LT)
Time of secondary increase of $J_{630}$	~19.58 UT (02.50 LT)	17.38 UT (00.30 LT)	19.04 UT (01.56 LT)	14.44 UT (21.36 LT)
Duration of the effect (min)	44	67	79	92
Intensity ( $J_{630}$ ) during of the effect (R)	~260	~200	~250	~175
Dst during a beginning of effect (nT)	−98	−10	−127	−141

(16.32–16.42 UT). The moment of  $J_{630}$  disturbance beginning during this event is difficult to be determined accurately because of weak variations in emissions registered about 7 min (16.32 UT) before the storm sudden commencement (16.39 UT). The second moment of the beginning of the 630 nm emission increase determined more reliably was recorded at about 16.42 UT. Coincidentally with the  $J_{630}$  increase, there was registered the increase in the 577.7 emission intensity and the increase of the signal in the spectral range between 360 and 410 nm (Afraimovich et al., 2002). In Fig. 3, the commencement of the main magnetic storm phase at about 18.00 UT is shown as an abrupt change of the magnetic field intensity at the geostationary orbit. Thus, the interval of this  $J_{630}$  disturbance at the initial MLA phase (WD interval) was practically localized between the sudden commencement and the main storm phase beginning and was coincident with the period of magnetosphere restructuring. Substorm processes accompanied by electron precipitation into the atmosphere developed as a response to the sudden commencement.

The  $J_{630}$  increase within the WD interval coincided with the abrupt motion of the auroral oval to the equator. For about 20 min after sudden storm commencement, the southern boundary of the auroral oval in the night sector moved from 61°N to 57°N, and then it remained in 56–57°N for a long time (Afraimovich et al., 2002). Since the width of the mid-latitude ionospheric trough covers 5–6°, we assume that at 16.30–17.00 UT the station for optical observations was in the vicinity of the southern trough boundary. At the same period according to the data from LANL 1994-084 satellite located at the geostationary orbit of 103.7°E longitude, an abrupt increase in precipitation of 50–150 keV electron was registered. The 630 nm emission maximum in the WD interval was coincident with the beginning of electron flow decrease at the geostationary orbit (this is not shown in figure).

### 3.2. October 2003 event

Fig. 4 presents data on variations of H-component of the geomagnetic field intensity in Irkutsk (lower panel) and at the geostationary orbit using the measurement from GOES-10 satellite (three upper panels) for the event on October 30, 2003. The magnetic storm that began at 18.00 UT on October 30, 2003 was the third of the strongest magnetic storms from the geomagnetic field disturbance series occurred on October 29 (Panasyk et al., 2004). The storm started on the background of the recovery phase of the second storm, when the Dst index had a value about  $-127$  nT; i.e., by the moment of WD interval beginning the magnetosphere was largely disturbed. Auroral activity increased gradually on the background of the ring current intensity decrease since 12.00 UT on October 30, 2003. By the moment of the mid-latitude aurora commencement, the AE-index increased from 200–300 nT at 12.00–13.00 UT to more than 2000 nT at 17.30–17.45 UT. By 17.00 UT in accordance with diurnal variation

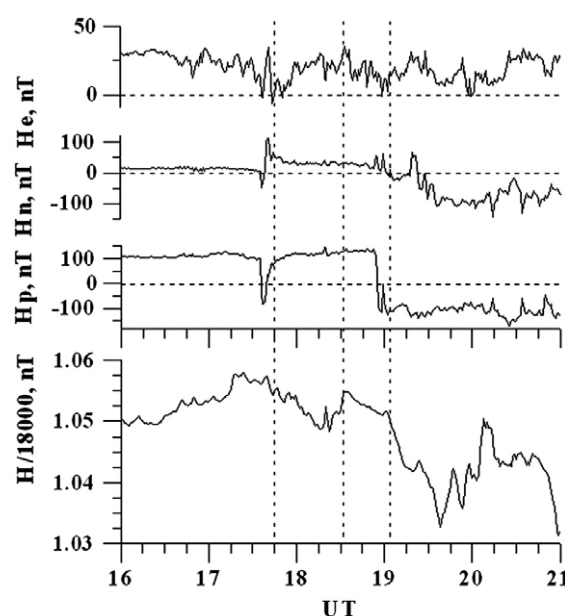


Fig. 4. Variations of geomagnetic field according to the measurements both at the geostationary orbit (GOES-10  $\lambda = 225^\circ\text{E}$ ) and at the ground level in Irkutsk for the initial mid-latitude aurora phase on October 30, 2003.

and due to increased auroral activity, the oval position in the Irkutsk longitude was displaced up to 58.6°N equatorwards (Fig. 5). Estimates based on the formulae, for high geomagnetic activity (Galperin et al., 1977; Gussenhoven et al., 1983), showed that by 18.00 UT the diffuse precipitation boundary moved equatorward to  $\sim 49^\circ\text{N}$  of the invariant latitude and continued to expand for the next 2 h (the Irkutsk invariant latitude is  $47^\circ\text{N}$ ). At the instant close to the beginning of the mid-latitude aurora observation in

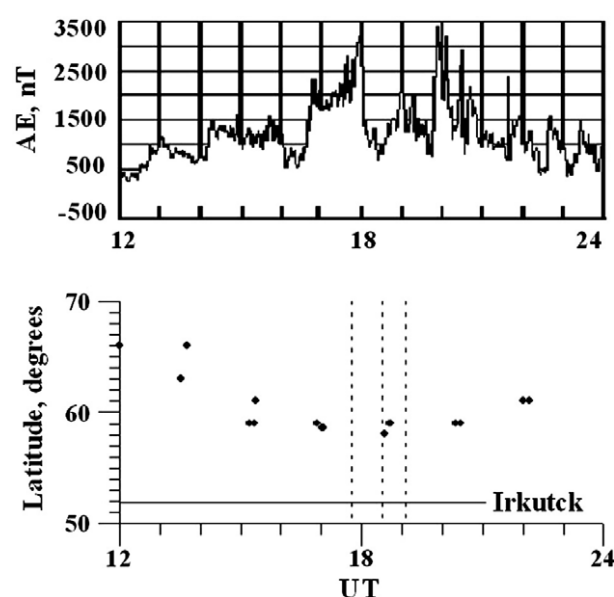


Fig. 5. Variations of AE-index of auroral activity (upper panel) and location of the equatorial boundary of auroral oval (lower panel) for the case of the mid-latitude aurora on October 30, 2003.



Irkutsk, several events occurred in the solar wind and Earth magnetosphere. From 17.35 UT till 17.40 UT (WIND satellite data), an abrupt short-term increase of the solar wind velocity was registered; and as a response to this event at 17.36 UT short-term geomagnetic field variations were recorded by GOES satellites. As deduced from observations in Irkutsk, an abrupt auroral activity rise also corresponded to the MLA commencement. At about the same time some decrease of the magnetic field H-component was observed. We may assume that these events resulted in the optical signature at the station that appeared within the region of defused radiation zone, whose equatorial boundary coincided with the plasmopause boundary for high geomagnetic activity (Starkov, 2000). As deduced from the WIND satellite data, high density ( $19\text{--}25\text{ cm}^{-3}$ ) and velocity ( $900\text{--}2000\text{ km/s}$ ) of the solar wind maintaining a high magnetosphere compression were observed in the circumterrestrial space for all the period of 17.45–19.15 UT considered; however, at the moment it is difficult to relate at the WD disturbance maximum in Irkutsk the specific events in solar wind. As deduced from measurements made in Irkutsk, the WD end was preceded by the local magnetic field overturn to the south at the geostationary orbit and by the beginning of a considerable magnetic field H-component decrease.

### 3.3. March 1991 and November 2003 events

Here, we will briefly describe MLA events for the magnetic storms of March 24, 1991 and November 20, 2003.

As evident from observations in Irkutsk, the mid-latitude aurora began at  $\sim 19.14$  UT on March 24, 1991 at the beginning of the main phase of the second magnetic storm in the series of geomagnetic disturbances on March 24, 1991, when the Dst index was reduced to  $\sim (-90)$  nT. Based on model calculations, the mid-latitude ionospheric trough minimum was displaced from  $50^\circ\text{N}$  to  $49^\circ\text{N}$  of the invariant latitude for the period 19.00–20.00 UT on March 24, 1991; and the station for auroral observations was brought closer to the diffuse precipitation zone (we used the calculation model for the mid-latitude ionospheric trough position from the paper Deminov et al., 1995). Note that over a long period (before, during and after the WD interval) a high auroral activity ( $\text{AE} = 800\text{--}2000$  nT) had been recorded. The MLA occurrence was registered simultaneously with the local magnetic field change at the geostationary orbit. The 630 nm emission intensity maximum in the WD interval may be correlated with some decrease of the auroral activity, while start of a new increase of the 630 nm emission intensity after the WD interval may be attributed to the beginning of abrupt change in the geomagnetic field based on geostationary orbit measurements, which are characteristic for abrupt ring current amplification.

The magnetic storm on November 20, 2003 is the strongest of the storms investigated (see Table 1). The main storm phase duration was about 11 h. MLA was registered

within about 4 h after the main phase commencement, when Dst had amounted up to  $\sim -170$  nT. Considerable changes had occurred in the magnetic field at the geostationary orbit as well as the auroral electrojet had been amplified before the mid-latitude aurora commencement. The beginning of the 630 nm emission intensity increase coincided with the decrease of geomagnetic field H-component value as deduced from measurements in Irkutsk. The auroral oval reached the latitude of about  $57^\circ\text{N}$  in the longitude of Irkutsk. As in the case on October 30, 2003, further amplification and then decrease of the AE-index did not result in a noticeable auroral oval motion poleward. Perceptible peculiarities in the magnetic field were not observed at the instant of the short-term emission intensity decrease. However, the moment of the maximal 630 nm emission intensity decrease (the end of the WD interval studied) and the beginning of further 630 nm emission intensity increase in MLA again coincided with the auroral electrojet amplification and the oval latitude decrease. Although less distinct than in the case of October 30, 2003, the MLA amplification is obviously related to the auroral electrojet amplification and to the shift of the auroral particle precipitation boundary to the equator.

## 4. Discussion and conclusion

From the analysis of the initial MLA phase during the four magnetic storms we can note the following. The instant of the wave-like disturbance commencement in the WD interval of the initial MLA phase coincides with the magnetosphere restructuring process and with the auroral oval motion equatorwards. The end of the wave-like disturbance of the 630 nm emission intensity in the WD interval and the beginning of the further considerable 630 nm emission intensity increase in MLA coincide with the appreciable ring current increase and with the further auroral boundary motion towards the equator. For the event on April 6, 2000 during the wave-like disturbance in the WD optical observation station was nearby the plasmopause projection whereas in other three events this station was near the diffuse precipitation boundary.

Mid-latitude auroras generally occur during magnetic storms with sudden commencements. In the magnetic storms on March 24, 1991 and November 20, 2003, such sudden commencements were observed several hours before the intervals analyzed. In the magnetic storm on April 6, 2000 the sudden commencement immediately antedated the initial MLA phase. The magnetic storm on October 30, 2003 is considered as a storm with a gradual commencement (Panasyk et al., 2004); but one should keep in mind that in the preceding day (October 29, 2003) a magnetic storm with the sudden commencement was also registered.

According to Tinsley et al. (1986), MLA excitation processes are closely related to the ring current development. The comparison between initial MLA phases of the magnetic storms under consideration and geomagnetic field

Dst variations points out that 630 nm emission disturbances singled out correspond to the time interval close to the beginning of the main storm phases, when the change-over to abrupt decrease of the Dst index value is noted. In the three events of four, Dst index was reduced to  $\sim -90$  nT and less by the moment of the mid-latitude aurora commencement. The analysis of the auroral oval equatorial boundary dynamics for MLA on October 30 and November 20, 2003 shows that by the beginning of disturbances in the 630 nm emission the oval boundary shifted equatorwards up to  $\sim 57$ – $58^\circ$ N and did not essentially move in space within the intervals of these disturbances. It is common knowledge that the diffuse aurora band that covers in average  $3$ – $5^\circ$  of the latitude and can get to  $10^\circ$  at high disturbance levels is situated more equatorwards than the auroral oval. In this case the optical observation station in the geographical latitude of  $52^\circ$ N may be brought into the region of the equatorial boundary of the diffuse glow band that, according to Starkov (2000), is projected on the plasmapause boundary in the night side. A number of papers discuss a particular role of the plasmasphere in the intensification of atmosphere emissions during MLA. So the intensification of the night airglow towards the equator from the diffuse auroral zone due to particles from the plasmasphere is considered in Ievenko et al. (1987). The overview (Gringauz and Bassolo, 1990) mentions the fact that the outer plasmasphere part can be observable as a thermal plasma zone that may appear in the airglow but has not been studied enough yet.

As for mechanisms of the 630 nm emission excitation in the time intervals singled out, we can note the following. In Rassoul et al. (1993), electrons with  $\sim 10$ – $1000$  eV energies are specified as a source of atmosphere emission excitation in mid-latitude “d” type aurorae that is closest in its morphological characteristics to the MLA analyzed. In Tinsley et al. (1986), superthermal electron flows ( $\sim 1$  eV) are also discussed. During the magnetic storm on October 30, 2003, the Irkutsk incoherent scattering radar providing height distribution of temperatures and electron density [<http://rp.iszf.irk.ru/hawk/orda/latest/latest.jpg>] was operating in the zone under study. It may be noted that at about 18.00 UT, when the excitation of the 630 nm emission intensity was registered in the WD interval, the electron temperature increase up to values of  $\sim 4000^\circ$ E and the electron density decrease were observed in the region of 450–550 km heights. In our case, this may indicate a possibility for exciting the 630 nm emission by superthermal electrons due to the upper atmosphere heating. The decrease of electron density  $N_e$  at the same time interval makes the situation under study similar to the phenomenon of SAR arcs, which are also related to a plasmapause, electron temperature  $T_e$  increase, and electron density  $N_e$  decrease in a SAR arc region (Cole, 1965). Origination of an added source of atmospheric 630 nm emission excitation (superthermal electrons) different from excitation mechanisms in the night airglow under quiet geomagnetic conditions (dissociative recombination reactions) can serve as a criterion for assign-

ing these disturbances properly to mid-latitude aurorae. An additional argument for this statement may be the fact that the rates of the 630 nm emission increase in WD and MLA intervals are equal (see Fig. 2).

Thus, having considered the 630 nm emission variations at the initial MLA phases during the strong geomagnetic storms and having compared them with magnetic–ionospheric parameters, we can draw the following preliminary conclusions:

1. At initial mid-latitude aurora phases in the 630 nm emission, short-term disturbances with amplitudes exceeding those of night airglow variations are singled out.
2. These disturbances can be observed at an initial storm phase and were accompanied by geomagnetic intensity variations as deduced from measurements at geostationary orbits.
3. The 630 nm emission disturbances singled out at the initial mid-latitude aurora phases can be related to the processes in the region of the equatorial boundary of the diffuse precipitation zone, plasmapause or outer plasmasphere part as well as to displacements of these structures above the optical observation station.
4. One of the possible excitation mechanisms of the atomic oxygen emission in the 630 nm line during the disturbances mentioned above can be a mechanism of collision excitation of oxygen atoms by superthermal electrons.

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