Characteristics of midlatitude aurorae during large geomagnetic storms within the current solar cycle

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We present the characteristics of most intense midlatitude aurorae in Eastern Siberia (52°N, 103°E), observed during large geomagnetic storms on April 6–7, 2000, March 31, 2001, and October 29–31 and November 20–21, 2003. Depending on the level of geomagnetic activity and phase of magnetic storm, the recorded midlatitude aurorae can be classified into different types of midlatitude aurorae: (1) d-type (with a predominant emission at 630 nm), (2) SAR arcs (630 nm), and (3) auroral type (558 and 630 nm) with the occurrence of sub-storm activity. We discuss the observed specific features of occurrence of midlatitude aurorae at specific times of the day (UT dependence) and their relation to the magnetic-ionospheric structures.

Introduction

The statistics of instrumented observations of midlatitude aurorae (MA) under high-level geomagnetic perturbations ($D_{st} \le -300$ nT) are restricted to a few cases.[1] By virtue of this situation, some features of observed midlatitude aurora types still remain the subject of research in recent publications.[2,3]

This paper presents some results of optical observations of the MA during large geomagnetic storms observed in the current solar cycle in south of Eastern Siberia (52°N, 103°E, Geophysical Observatory of the Institute of Solar-Terrestrial Physics SB RAS).

Instrumentation and observation technique

The optical radiation of the upper atmosphere was measured using zenith-looking photometers with swinging interference filters ($\Delta\lambda_{1/2} \sim 1$–2 nm) at the emission lines of atomic oxygen, of 558 and 630 nm wavelengths. In addition, we recorded emission in the near infrared (720–830 nm) and ultraviolet (360–410 nm) regions of the spectrum. The spectral intervals 360–410 and 720–830 nm were separated out by absorption filters. The angular fields of view of the photometer channels were 4–5°. The absolute calibration of measurement channels of instruments have been performed using reference stars and was controlled using reference light sources in twilight and morning hours of observations. The software of photometer allowed us to record the data of photometric channels with ~ 12-s time averaging. When pulsed signals in excess of a preset threshold were detected, there was a possibility of signal recording with time resolution of ~ 8 ms.

Observation results

As known, one of the dominating emissions in MA is the emission of atomic oxygen at 630 nm. Depending on the level of geomagnetic perturbations, storm phase, and latitude of the observation point, this emission may have specific features for different types of midlatitude aurorae.[2] Table presents the characteristics of magnetic storms, maximum values of K_p index ($K^{max}{}_{,p}$), A_p indices, minimum values of D_{st} index ($D^{min}{}_{,st}$) during the storm, and maximum values of zenith intensities of emissions at 558 and 630 nm ($I^{max}{}_{,558}$ and $I^{max}{}_{,630}$) during MA, recorded at the geophysical observatory of Institute of Solar-Terrestrial Physics SB RAS in recent years.

The MA events during magnetic storms on October 29 and 30, 2003 were recorded under overcast cloud conditions; therefore, also given in the table (in the column of maximum intensity of 630 nm emission) are intensities reduced to the clear-sky emissions.

Date	Storm type	$K^{max}{}_{,p}$	A_p	$D^{min}{}_{,st}$, nT	$I^{max}{}_{,630}$, kRl	$I^{max}{}_{,558}$, kRl	Storm phase
03/24/1991	G4	9_-	161	−281	~2.6		Pri
03/25/1991		9_-	130	−298	~0.6		Sec
02/03/1992	G4	8_-	92	−170	~0.3		Sec
04/06/2000	G4	8_+	82	−287	~2.77		Pri
04/07/2000		9_-	74	−288	~0.5		Sec
03/31/2001	G4	9_-	192	−358	~3.1	~1.5	Sec
10/21/2001	G4	8_-	57	−166	~0.57		Pri
10/22/2001		7_+	96	−166	~0.67		Sec
10/29/2003	G4	9_-	204	−345	≥ 2.9 (4.3–7.1)		Pri
10/30/2003	G5	9_0	191	−401	≥ 4.3 (6.4–10.5)		Pri
11/20/2003	G4	9_-	150	−465	~19.4	~11.1	Pri

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From the table it follows that most intense MA events in the current solar cycle were recorded during the following four magnetic storms: on April 6–7, 2000; on March 31, 2001; and on October 29–30 and November 20–21, 2003.

Midlatitude aurora during magnetic storm on April 6–7, 2000. The highest values of the 630-nm emission intensity (I_{630}) were recorded in time interval 18:00–21:00 UT during the main phase of the magnetic storm.[4] Perturbations of the 558-nm emission and in the spectral channel 360–410 nm are not distinctly seen; they were recorded only at times of most intense growth of 630 nm emission. The amplitude of I_{630} perturbations on April 7, 2000, during the recovery phase, was much lower and has been interpreted as SAR arc.[5]

Midlatitude aurora during magnetic storm on March 31, 2001 was recorded during the recovery phase. The main phase of this magnetic storm took place daylight at the observation point. This explains why there are no data of the optical observations for the main phase of this storm. In Refs. 6 and 7, the perturbations of 630-nm emission in the time interval 14:00–15:30 UT are interpreted as intense SAR arc. Perturbations of the atmospheric emissions in the time interval 15:30–21:30 UT, correlating well with sub-storm activity at high latitudes, are attributed to invasion of high-energy auroral electrons. The dominating emissions in this time interval (in addition to 630-nm emission) are also the emission of atomic oxygen at 558 nm and emission in the spectral region from 360 to 410 nm.

The midlatitude aurorae during magnetic storms on October 29–30 and November 20–21, 2003 corresponded to the extreme geomagnetic perturbations. The midlatitude aurorae on October 29 and 30, 2003 were preceded by two strongest solar flares of X17.2 and X10.0 classes correspondingly on October 28 and 29, 2003. These flares have been ranked the most powerful solar flares recorded since 1976 (http://www.spaceweather.com/solarflares/topflares.html); they have been the source of two sequential large geomagnetic storms on October 29 and 30, 2003 with minimum values of $D^{\min}{}_{,st}$ index, respectively, –345 and –401 nT, and maximum K_p index of 9_0.

The midlatitude aurora on November 20, 2003 was preceded by a series of solar flares on November 17–18 of the M class; it has been the source of strongest (in this cycle of solar activity) magnetic storm with $D^{\min}{}_{,st} = -465$ nT and $K_p = 9_-$.

For the MA events on October 29 and 30 and November 20, 2003, the beginning of growth of the intensity of 630-nm emission and of maximum I_{630} values corresponded to the main phases of the magnetic storms. The midlatitude aurora on November 20, 2003 overlaps with the beginning of the recovery phase. The dominating emission of MA on October 29 and 30, 2003 was the 630-nm emission. The largest variations of the emission at 558 nm and light fluxes in spectral channels 360–410 and 720–830 nm are observed in time intervals of rapid increases of intensity of 630 nm emission. In midlatitude aurora on November 20, 2003, the second dominating emission is the 558-nm emission, whose perturbations appear to be shifted in time relative to the perturbations of the 630-nm emission. The variations in the spectral channels 360–410 and 720–830 nm mostly echoed those of 558-nm emission.

The recorded maximum intensities of 630-nm emission during MA on October 30 and November 20, 2003 are the highest over the entire period of optical observations at geophysical observatory of Institute of Solar-Terrestrial Physics SB RAS (1989–1993 and 1997–2003). This is also true for the perturbations of 558-nm emission recorded during the MA on November 20, 2003.

Discussion

The considered MA events, observed in the main phases of magnetic storms on April 6, 2000 and October 29–30 and November 20, 2003 have a common feature associated with the time of their observation, performed in the second half of night. Figure 1 presents the curves of nighttime behavior of the atmospheric emission at 630 nm for these dates.

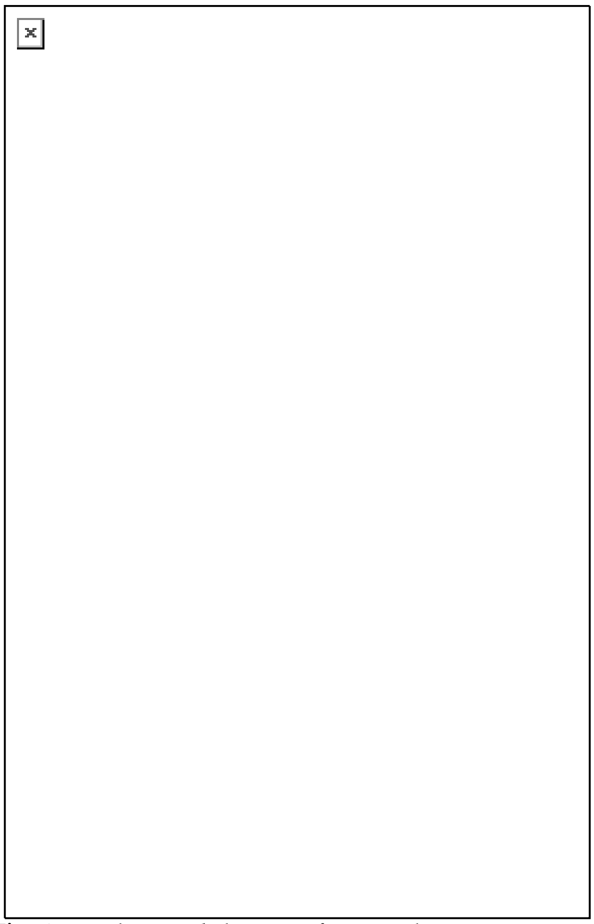

Fig. 1. Nighttime behavior of atmospheric emission at 630 nm during midlatitude aurorae in the main phase of the magnetic storms.

Local midnight corresponds to 17:00 UT and is indicated by vertical dashed line. The above-mentioned feature is also characteristic of the less intense MA on October 21, 2001. The specific feature of the MA observation in the second half of the night during the main phases of the magnetic storms observed at the geophysical observatory of the Institute of Solar-Terrestrial Physics SB RAS was already noted in Refs. 4 and 8, and was associated with the correlation between I_{630} and D_{st} index of variations of the geomagnetic field during geomagnetic perturbations and pronounced UT dependence of D_{st} index. The dependence of I_{630} on D_{st} index during geomagnetic storms has a physical interpretation associated with the interaction of intensifying circular current (which determines the D_{st} variations) with plasmosphere, the result of which may be intensification of fluxes of plasma from the plasmosphere to ionosphere thus causing the heating of the ionosphere.

The recovery phases of magnetic storms on April 7, 2000 and March 31, 2001 had different nighttime behavior of the 630-nm emission, typically with predominance of the most pronounced perturbations of I_{630} in the first half of night. Figure 2 presents the curves of nighttime behavior of the 630-nm emission on April 7, 2000 and March 31, 2001. For a comparison, we also give the curve of nighttime behavior of this emission on March 25 during large magnetic storm on March 24–25, 1991 of the previous solar cycle.

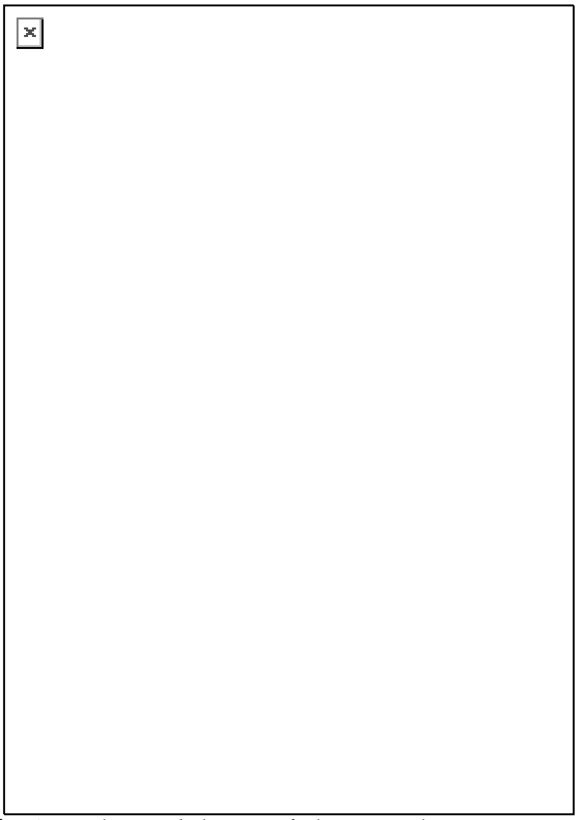

Fig. 2. Nighttime behavior of the atmospheric emission at 630 nm during midlatitude aurorae in the recovery phase of magnetic storms.

According to Ref. 2, the main types of midlatitude aurorae with dominating emission at 630 nm are projected onto the region of plasmopause. Because of the latitudinal location of the observation point it is possible to observe the midlatitude and sub-auroral ionospheric structures and their optical manifestations associated with the growth of magnetic activity. For the increasing level of geomagnetic perturbations, this primarily must lead to transition from the region of midlatitude aurora of the atmosphere to the region of diffusion-type aurora, located closer to equator than to auroral zone and spanning latitude intervals of 3–5° and larger.[9] It is noteworthy, according to Ref. 10, that it is possible to distinctly see "thinner" plasma boundaries at heights of the upper atmosphere and their natural projections onto the magnetosphere: aurora of nighttime sky – plasmosphere, equatorial boundary of weak diffusion-type auroral emission – plasmopause, diffusion-type auroral zone – remnant plasma layer, and the region of circular current.

In this regard, perturbations of the 630-nm emission in the main phases of magnetic storms with characteristic timescale ~1 h and emission intensity ratio $I_{630}/I_{558} > 1$ may reflect the projection of plasmopause and, in accordance with the classification of midlatitude aurora types,[2] may be classified as aurorae of d type, whose source are electrons with energies ~ 10–1000 eV.

Perturbations of the 630-nm emission occurring during the recovery phase of magnetic storms on April 7, 2000 and March 31, 2001 in time intervals 14:00–15:30 UT are interpreted in Refs. 5–7 as SAR arcs. An observation of SAR arcs at night in Asian region has also been reported in Ref. 3. Quite close resemblance of curves in Fig. 2 makes it possible to suggest that the perturbation of the 630-nm emission on March 25, 1991 in the first half of night (14:00–15:00 UT) can also be caused by a SAR arc. The SAR arcs are recorded mainly during the recovery phases after the magnetic storms; they are also observed in projections of plasmopause, while their source are electrons with energies < 10 eV.[2]

Of special interest are the MA events, in which the dominating emission is the emission of atomic oxygen at 558 nm, the events we conventionally classified as auroral-type MA. Figure 3 shows the behaviors of 558- and 630-nm emissions and emission in the spectral band 360–410 nm during the MA on November 20, 2003. We already reported earlier that at midlatitudes a perturbation of this emission (up to values ~1.5 kRl) was recorded during the sub-storm perturbations during large magnetic storm on March 31, 2001.[6,7] In Refs. 6 and 7, the perturbation of 558-nm emission was attributed to invasion of electrons of auroral-level energies. It should be noted that Ref. 2, proposing a classification of observed types of midlatitude aurorae, discusses a number of types of midlatitude aurorae and in none the 558-nm emission is considered as a dominating emission. Probably, such perturbations of the 558-nm emission at midlatitudes are characteristic only of the intense magnetic storms, and the statistics of their observations is limited. We have found in the literature only one paper, which described analogous perturbation of 558-nm emission during a magnetic storm at lower latitudes.

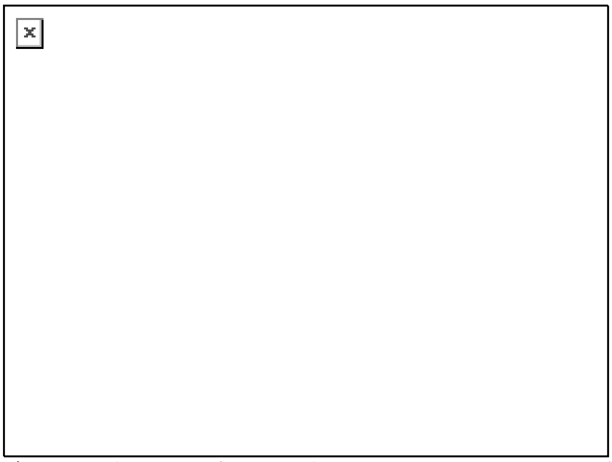

Fig. 3. Behaviors of atmospheric emissions at 558 and 630 nm, and emission in the spectral channel of 360–410 nm during midlatitude aurora on November 20, 2003.

For instance, Ref. 11 reports that intense magnetic storm occurred on October 21, 1989 ($K^{max}_{p} = 8_{+}$, $D^{min}_{st} = -268$ nT) in the northern part of the sky over Hokkaido island (44°N, 142°E), and that the intense red midlatitude aurora was observed in this period. The intensity of 558-nm emission remained at its usual level, except for a rapid spike within ~ 8 min. Miyoka Hiroshi et al.,[11] maintain that such aurorae at such low latitudes are observed once every 20 years.

During the MA on November 20, 2003 we also observed perturbations in the spectral range 360–410 nm, which can be interpreted as the occurrence of emission of N_2^+(1NG) with the wavelength of 391.4 nm, usually observed in polar aurorae as a result of ionization of molecular nitrogen by the electrons. Here it is worth noting that, as argued in Ref. 9, in diffusion-type aurora there is practically no aurora in the band of N_2^+(1NG), while the intensity of 630-nm emission is 4 times higher than the intensity of 558-nm emission, implying the soft spectrum of the electrons invading during the diffusion-type aurora. During the MA on November 20, 2003, the intensity of 558-nm emission in a certain time interval exceeded that of 630-nm emission, which, as in the case of magnetic storm on March 31, 2001,[6,7] may be an indirect indication of invasion of electrons of the auroral-level energies. In this case, the MA on November 20 possesses the features typical for usual polar aurorae.

According to Ref. 1, the usual polar aurorae do not migrate to latitudes lower than those corresponding to L envelops ~2.7. The L envelop corresponding to the geophysical observatory is less (L ~ 2), suggesting that ionospheric and magnetospheric structures had longer excursions during the magnetic storm on November 20–21, 2003, possibly corresponding to a limiting oblate shape of the magnetosphere.[1] From the ratio between I_{630} and D_{st} index of variations of the geomagnetic field during the geomagnetic perturbations, and from analysis of the table it is possible to draw one more conclusion about the MA on November 20–21, 2003. The minimum value of D_{st} index of –465 nT, observed during the MA on November 20–21, 2003, can be classified as the extreme one over the entire period of instrumented observations. Over the period from 1957 until 2003, only one magnetic storm (on March 13–14, 1989) had smaller D_{st} values. The geomagnetic storm on February 11, 1958, accompanied by great planetary midlatitude aurora, had minimum value of D_{st} index of –426 nT. The recorded maximum intensities of 630-nm emissions during the MA on November 20, 2003 had the largest values over the entire period of optical observations at the geophysical observatory of the Institute of Solar-Terrestrial Physics SB RAS (1989–1993 and 1997–2003). This is also true for perturbation of the 558-nm emission, recorded during the MA on November 20, 2003. In this regard, probably, the MA on November 20, 2003 can also supplement the list of Great aurorae discussed in a number of publications (see, e.g., Ref. 12).

Conclusions

Depending on the level of geomagnetic activity and the phase of magnetic storm, the midlatitude aurorae, recorded in East Siberia, during strong magnetic storms can be classified into different types of midlatitude aurorae: (1) d type (with predominance of the emission at 630 nm), (2) SAR arcs (630 nm), and (3) auroral type (558 and 630 nm), each characterized by an individual spectral composition of dominating emissions and their intensities, each having specific probability of recording during night, and reflecting a current state or dynamics of the magnetospheric-ionospheric structures and their projections onto the upper atmosphere.

From the recorded characteristics of the midlatitude aurora on November 20, 2003 during the gigantic magnetic storm, and from statistics of the magnetic storms in terms of D_{st} index and its correlation with the intensity of 630-nm emission during geomagnetic perturbations it is possible to conclude that the midlatitude aurora on November 20, 2003 can be classified as the extreme one among the observed events, both for location of geophysical observatory of the Institute of Solar-Terrestrial Physics SB RAS and other midlatitude zones.

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