Night airglow variations over Eastern Siberia during March 31 – April 4, 2001, magnetic storm

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Unusual observations of intense night airglow emissions at mid-latitudes (52°N, 103°E) during a major magnetic storm of March 31 – April 4, 2001, are examined. The glow intensity in the 630 nm and 558 nm lines was as high as 3.5 and 1.5 kRl, respectively. Optical observations are compared with satellite data on precipitating energetic electrons and airglow soft X-ray emissions, as well as with ground-based observations of geomagnetic field and ionospheric conditions acquired at the longitude of the optical observations. It is concluded that the intense airglow emissions at 558 nm and in the spectral band of 360–410 nm was caused by high-energy auroral electrons precipitating into the atmosphere, and glow variations are connected with the plasma sheet dynamics during the storm. The 630 nm emission disturbances are mainly due to heating of the ionospheric *F*-region by soft electrons and in some periods they are interpreted as an intense SAR-arc. The dynamics of ionospheric and magnetospheric structures during the storm that determines the main optical characteristics of mid-latitude airglow emissions is discussed.

Introduction

Dominant mid-latitude airglow emissions usually include 630 nm atomic oxygen emission and N_2^+ molecular bands of the first negative system.[1–3] According to the data of optical observations,[4] during a strong magnetic storm on March 31 of 2001 in Southeastern Siberia (52°N), observers noticed short significant disturbances in the atomic oxygen 558 nm line that were not correlated in time with variations of the 630 nm emission. In Ref. 4 it was assumed that the recorded short events of intensified 558-nm-wavelength emission and N_2^+ (391.4 nm) emission are connected with precipitation of high-energy particles from the magnetosphere into the mid-latitude atmosphere during sub-storms and the events similar, to some extent, to "usual" auroras. This assumption contradicts somewhat the results (see, for example, Ref. 5) reporting the limit equatorial latitudes for observation of usual auroras.

In this paper, we analyze thoroughly the variations in airglow emissions observed in the Geophysical Observatory of the Institute of Solar-Terrestrial Physics SB RAS (Tory village, 52°N, 103°E; CGMC geomagnetic coordinates 47°N, 176°E) in the period of the March 31–April 4, 2001, magnetic storm also using the satellite data (LANL: http://leadbelly.lanl.gov/lanl_ep_data/ep_request.html, DMSP: http://sd-www.jhuapl.edu/Aurora/ovation/ovation_display.html, NOAA: http://sec.noaa.gov/pmap/pmapN.html, POLAR: http://pixie.spasci.com/pixie/homepage/img_dir/archive/2001/Mar) on variations in the flows of energetic particles in the magnetosphere and airglow soft X-ray emission, as well as ground-based data on the state of the ionosphere and geomagnetic field at high and middle latitudes on the longitude of ground-based optical observations.

Experiment

Airglow observations were conducted with a zenith photometer by the technique described in Ref. 3. Figure 1 shows the situation in the geomagnetic field and solar wind during the global magnetic storm. The intervals of optical observations are shown in Fig. 1 by bold bars along the abscissa. The geomagnetic storm was caused by the dense cloud of solar wind plasma approaching the Earth. In the period since 00 UT until 01.00 UT the density of the solar wind plasma achieved the record value of 101.9 cm^{-3} at the solar wind velocity of 526 km/s. The magnetic storm outbreak was recorded at 00.51–00.56 UT. According to data of the Irkutsk magnetic station (52.3°N, 104.3°E), the main phase of the magnetic storm took place in the period of 03.36–08.42 UT. During the main phase, the solar wind density was higher than 70 cm^{-3} at the velocity higher than 700 km/s. At the peak of the main phase, the indices of geomagnetic field disturbance Dst and Kp achieved the values of –358 nT and 9–, respectively. According to the NOAA classification (http://sec.noaa.gov/NOAAscales/index.html), this magnetic storm can be classified as an extreme one. Such magnetic storms are very rare geophysical phenomena: in the period since 1957 to 2001 only five magnetic storms had the Dst index lower than this value.

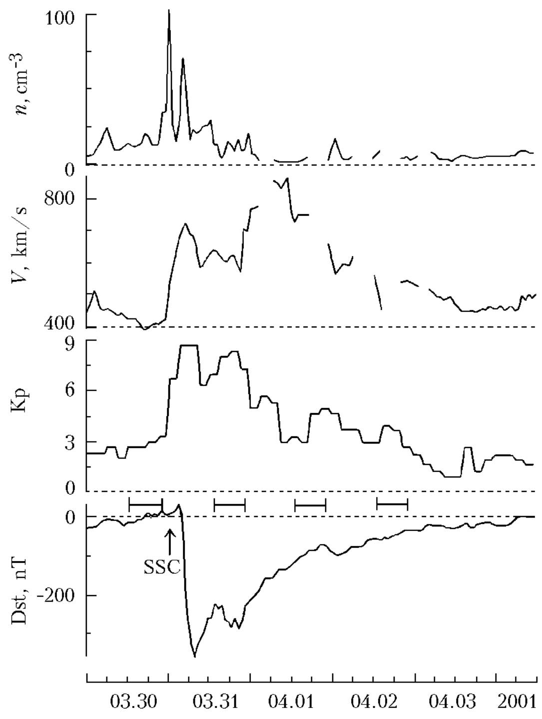

Fig. 1. Situation in the Earth's geomagnetic field and solar wind for the period of March 31–April 04, 2001, event: n is the solar wind plasma density; V is the solar wind velocity; Kp and Dst are indices of geomagnetic field disturbance.

Observations

The results of optical observations are shown in Fig. 2. It can be seen that the intensity of airglow emissions on March 31 of 2001 was extremely high: 3.5 and 1.5 kRl for the 630 and 558 nm emissions, respectively. As compared with the airglow before the magnetic storm on March 30 of 2001 (curves *1*) and on April 1 of 2001 (curves *3*), the intensity of the observed emissions at the beginning of the storm reconstruction phase on March 31 of 2001 (curves *2*) was several times higher, for the 630 nm the excess was more than 15 times. According to the airglow variations observed in different optical regions, the whole observation period on March 31 can be divided into several periods: 14.00–15.30, 15.30–17.40, 17.40–19.10, and 19.10–21.30 UT. These periods are marked by Roman figures and are shown by vertical dashed lines in Fig. 2.

Figure 2*d* depicts variations in the position of the equatorial boundary of the statistical auroral oval at some moments on ~103°E. The position of the boundary was determined according to data of the http://sec.noaa.gov/pmap/pmapN.html website by the level of precipitating electron flows ~ 0.1 erg/cm^2·s.

Figure 3 depicts variations of the auroral electrojet AE index, the indicator of the substorm activity in the magnetosphere, variations in the value of absorption of extraterrestrial radio noise A in the ionosphere according to observations at the subauroral Norilsk geophysical observatory (69°N, 89°E) – indicator of the electrons with the energy > 40 keV invading the high-latitude atmosphere, flows of the omnidirectional electrons I with the energy of 50–75 keV recorded by the geostationary satellites LANL 1991–084 located at 102.7°E (curve *1*) and LANL 1994–080 at 195.7°E (curve *2*), and variations of the 558 nm emission.

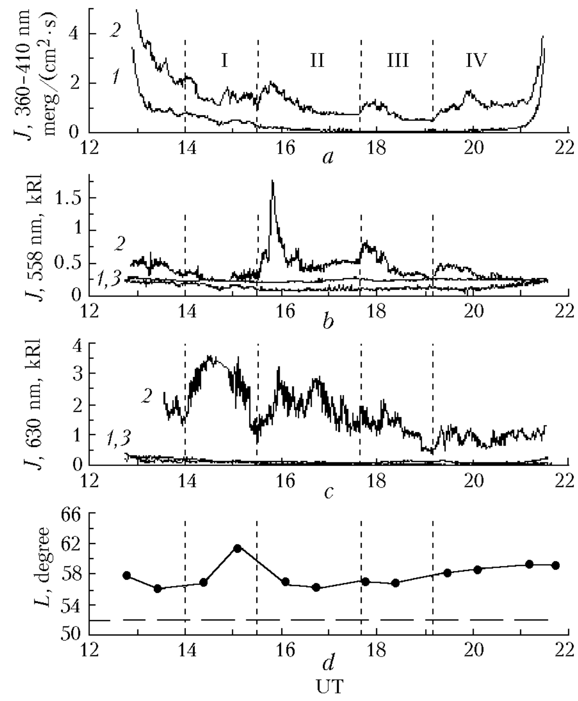

Fig. 2. Variations of the airglow intensity J above the Tory village on March 30–April 1 of 2001 in the 360–410 nm spectral band (*a*), atomic oxygen 558 nm (*b*) and 630 nm (*c*) lines and position of the equatorial wall of the auroral oval (*d*). The dashed line in Fig. 2*d* shows the latitude of the geophysical observatory of ISTP SB RAS.

Compare the data of optical observations with the geophysical situation in the period of 14.00–21.30 UT. A characteristic feature of optical data in the period of 14.00–15.30 is disturbance of the 630 nm emission intensity J at insignificant variations in the 558 nm airglow. The intensity of the 630 nm emission was high during the whole period, varying from ~ 1.5 kRl at 14.00 UT up to the maximum value ~ 3.5 kRl at 14.30 UT and again falling down to 1.2 kRl at 15.30 UT.

It can be seen from Fig. 1 that the first part of the analyzed period (14.00–15.00 UT) falls on the decreasing ring current. In the period of 15.00–16.00 UT, we can see again the intensification of the ring current coinciding with some increase in the solar wind density. As a consequence of slow reconstruction of the magnetospheric structure, the auroral oval boundary begins to shift to higher latitudes (Fig. 2*d*). Since 14.13 until 15.04 UT the oval boundary shifted by 6.5° to the pole. However, already at 16.04 UT due to intensification of magnetospheric disturbance, the oval boundary again was on the geographic latitude of ~ 56°N. Since 14.27 UT until 15.25 UT, substorm disturbance of the auroral magnetosphere was observed, but it did not lead to some large disturbances in the region of 90–110°E. The geostationary satellite located at 102.7°E recorded no significant variations in the electron fluxes with the electron energy of 50–75 keV, and in Norilsk (on the longitude of 89°E) no ionospheric disturbances connected with precipitating electrons with the energy > 40 keV were observed. That is, the period of 14.00–15.30 UT was relatively calm for the longitude of observation in this experiment.

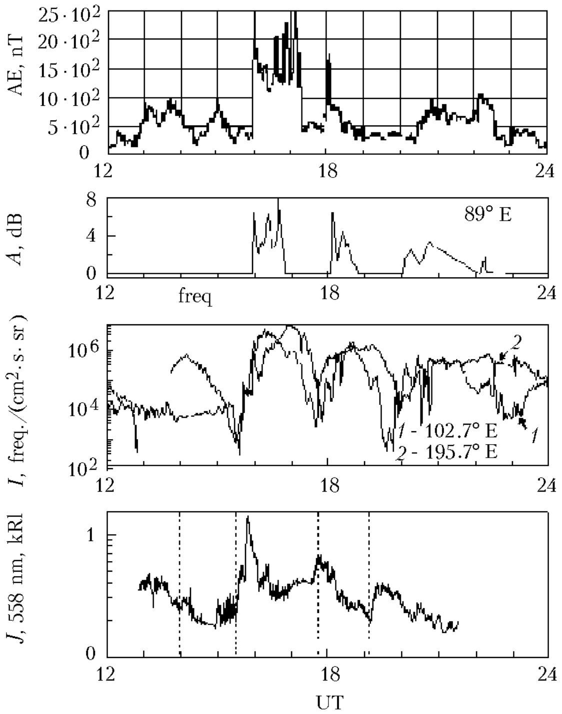

Fig. 3. Geophysical situation for the period of 12–24 UT on March 31 of 2001.

The period of 15.30–21.30 UT includes three separate intervals (see Fig. 2). Each of them began with sharp increase in the intensity of 558 nm line and 360–410 nm band emissions followed by its gradual decrease by the end of the interval. The highest increase in the intensity of the 558-nm line was observed in the interval of 15.30–17.40 UT, and then with every next interval the intensity decreased. Appearance of the fluxes of high-energy particles according to the data of geostationary satellites, variations of the geomagnetic field and absorption of radio noise according to the data of Norilsk station undoubtedly indicate development of substorms in these periods. From Fig. 3 we can clearly see rather close correspondence between the increase in the airglow intensity according to observations in the Tory village and the magnetospheric substorm distortions.

It follows from Fig. 3 that after the minimum of geomagnetic distortions (by the AE index) the auroral electrojet began to develop at 15.25 UT and achieved its maximum intensity of about 500 nT at 15.39–15.40 UT. The electron flux began to grow at 15.31 UT at the longitude of 195.7°E (Fig. 3*c*) and several minutes later at the longitude of 102.7°E. Since the equatorial boundary of airglow soft X-ray emission well coincides with the boundary of usual auroral airglow in the visible spectrum,[6] the spatial characteristics of soft X-ray airglow can serve as a good indicator of the dynamics of the magnetospheric disturbance region. According to the POLAR satellite data, at 15.20–15.25 UT weak X-ray emission was observed roughly at 170–210°E. For the next 5 min the airglow intensity increased (beginning of a magnetospheric substorm) and the airglow region boundary shifted to the west roughly to 110°E. At 15.33–15.40 UT the intensity of soft X-ray emission increased sharply, and the airglow region extended much deeper to the west that the longitude of the Tory village and to the equator.

The intensity of the 558 nm emission began to increase at 15.32 UT and peaked at 15.40 UT (see Fig. 2), which, on the one hand, confirms the conclusions[6] on the close relation between the regions of visible and X-ray airglow and, on the other hand, shows that the airglow emission recorded in the Tory village in the beginning of the second interval is a manifestation of the magnetic substorm being caused by the precipitation of electrons of auroral energies into the mid-latitude atmosphere. The highest peak of the 558 nm emission at the simultaneous peak increase of 630 nm and 360–410 nm emissions was observed at 15.49 UT. This coincides in time with the intensification of the X-ray emission at 15.48–15.50 UT and extension of the airglow region to the equator.

Comparing the 558-nm and 630-nm emissions (Figs. 2*b*,*c*), we can notice that their time behaviors are not fully correlated. In the interval of 16.30–17.12 UT, as the 630 nm emission intensity increases up to almost 3 kRl by 16.48 UT, the 558-nm emission intensity remains almost unchanged. We can conclude that besides the direct mechanism of airglow excitation by precipitating auroral-energy electrons there are some other mechanisms of excitation of the emission in the red line. Note that the equatorial boundary of the statistical auroral oval (Fig. 2*d*) at 16.44 UT was ~4° closer to the pole relative to the observation site and precipitations of auroral electrons were likely lacking. Consequently, the increase in the 630-nm emission could be connected with either soft electrons of the inner edge of the plasma layer or other mechanisms of emission excitation at 630 nm. Note also that the minimum of ionization in the main trough for the considered interval calculated by the model from Ref. 7 was several degrees closer to the equator relative to the observation site.

Analysis of the emission distortions in the following intervals (17.40–19.10 and 19.10–

21.30 UT) also allows us to believe that they are caused by precipitation of auroral-energy electrons into the atmosphere.

Discussion

One of the mechanisms causing the increase in the concentration of excited oxygen atoms $O(^1D)$ and intensification of the 630 nm emission in the mid-latitudes during geomagnetic storms is associated with heating of the F-region of the ionosphere due to increase of fluxes of superthermal electrons (~10–1000 eV) from the plasmasphere,[1,2,8] where the energy exchange occurs between the thermal plasma and the increasing ring current, which, in its turn, determines the Dst variations. In SAR-arcs forming in the region of the equatorial wall of the main ionospheric trough, excitation of oxygen atoms to the $O(^1D)$ state occurs largely in collisions with thermal electrons heated up to high temperatures. By now several possible sources of heating of ionospheric electrons in the region of SAR-arc airglow are proposed, namely, Coulomb collisions with hot ions of the ring current,[9] Landau damping of electromagnetic ion-cyclotron waves generated at interaction of the plasmasphere with the ring current,[10] low-energy component (< 10 eV) of precipitating particle fluxes,[2,11] and others.

The position of the minimum of the main ionospheric trough at the change of the geomagnetic activity into the reconstruction phase of the March 31, 2001, geomagnetic storm as estimated by the empirical models from Ref. 7 shows that the Tory village was 2–4° closer to the pole relative to the minimum of the main ionospheric trough. On the other hand, it can be seen from Fig. 2*d* that in the observation period the auroral oval was shifted to the pole from the observation site. Taking into account that both the models of the ionospheric trough and the statistical auroral oval give only their probable position, we can conclude that the Tory village for the observation period on March 31, 2001, was in the main ionization trough near the polar wall.

As in the period of 14.00–15.30 UT, when the 630 nm emission was disturbed most strongly, no substorm activity and increase in the fluxes of auroral-energy particles were observed (see Fig. 3), we can assume that the 630 nm emission was excited by the low-energy electrons forming the SAR-arc in the region of the main ionospheric trough and plasmapause.

As known, a SAR-arc may be up to several hundreds of kilometers (~ 600 km) wide,[12] corresponding to several degrees in latitude. Taking into account the dynamics of 630-nm airglow emission intensity and the dynamics of the equatorial edge of the auroral oval, we can assume that the SAR-arc until 14.00 UT had more equatorial position than the observation station, and starting from 14.00 UT its polar part overlapped the field of view of the zenith photometer, reaching the maximum overlapping at 14.30 UT, and then it again shifted toward the equatorial latitudes.

Thus, the peculiarities of airglow observation in Tory village and the accompanying geophysical situation suggest that an intense SAR-arc was observed at the latitude of Tory village in the period of 14.00–15.30 UT on March 31, 2001.

Some cases of SAR-arc observation in mid-latitudes of the Asian region at high levels of geomagnetic disturbance have been described in Refs. 13 and 14; one of these cases is similar to the analyzed magnetic storm of March 31, 2001. Thus, the data presented in this paper and Refs. 13 and 14 allow us to determine the limiting geomagnetic latitudes of the SAR-arcs observed by now in the Asian region ~ 45–47°.

The burst of the 558 nm emission at the time ~ 15.45 UT (first substorm) was preceded by a sharp shift of the equatorial boundary of the auroral oval toward the equator. This can be a result of motion of the plasma layer to the plasmasphere, whose invasion caused precipitation of high-energy particles. If we assume that the observed disturbances of the 558-nm emission are connected with the dynamics of the plasma layer, then the observed mid-latitude airglow has some features typical of usual auroras.

According to Ref. 5, usual auroras are not observed at the latitudes lower than that of the L-shells ~ 2.7, while SAR-arcs can shift up to $L \sim 1.7$. According to NOAA data (http://www.sec.noaa.gov/Aurora/index.html) the equatorial boundary of auroras at the highest level of geomagnetic disturbance in the Asian region corresponds to ~ 48° CGMC latitude. The CGMC latitude of 47° and the corresponding L-shell ($L \sim 2$) of the observation station in Tory village are indicative of significant shifts of ionospheric and magnetospheric structures in the period of March 31, 2001, magnetic storm, possibly corresponding to the limiting compression of the magnetosphere.[5] Such disturbances of the 558-nm emission in mid-latitudes are likely characteristic of only intense magnetic storms and statistics of their observations is limited. We succeeded in finding only one paper describing similar disturbance of the 558-nm emission during a magnetic storm in lower latitudes. Thus, during the strong October 21, 1989, magnetic storm ($Kp^{max} = 8+$, $Dst^{min} = -268$ mT) the intense mid-latitude red airglow was observed in the northern part of the sky over Hokkaido (44°N, 142°E).[15] The intensity of the 558-nm airglow emission was at the usual level, except for an 8-min burst. Hiroshi et al.[15] believe that such auroras in low latitudes are observed once in 20 years.

Conclusions

Thus, we can draw the following conclusions:

– The observed disturbances in the mid-latitude airglow on March 31, 2001, are caused by different-energy electron fluxes, reflecting the dynamics of projections of different structure elements of the magnetosphere at the magnetic storm reconstruction phase. The total level of the 630-nm emission may be caused by superthermal fluxes of plasmasphere electrons. Disturbance of the 630-nm emission in the period ~ 14–15.5 UT is interpreted as an intense SAR-arc (projection of plasmapause).

– Disturbances of the 558 and 391.4-nm emissions closely correlating with the substorm are likely caused by precipitation of aurora-energy electrons and connected with the dynamics of the plasma layer.

– Peculiarities of the 558-nm emission disturbance in the period of substorms and its characteristic intensities (~ 1 kRl corresponding to the auroral class I by the international brightness coefficient) allow us to formally classify this airglow, at least in some periods, as ordinary auroral forms.

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