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MID-LATITUDE AURORAS OF THE SOLAR CYCLE 25 ACCORDING TO OPTICAL INSTRUMENTS OF THE NATIONAL HELIOGEOPHYSICAL COMPLEX

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Abstract
Mid-latitude auroras (MA) are a rare geophysical phenomenon, however, according to some researches subvisual MA are observed more often. In addition, the observation of stable red auroral arcs (SAR arcs) in mid-latitudes was previously considered an extremely rare phenomenon. During regular observations at the Geophysical Observatory ISTP SB RAS (103°04`31" E 51°48`38" N) within the solar cycles 23 and 24, SAR arcs were recorded only for the four geomagnetic storms.

Optical instruments of the National Heliogeophysical Complex (NHC) at the beginning of the cycle 25 of solar activity (from April 2021 to March 2024 inclusive) registered 34 MA. Of these, 21 cases, structures corresponding to SAR arcs were observed in the airglow. It is worth noting that in at least one case, a SAR arc was observed with additional weak emissions at 557.7 nm and 427.8 nm. In addition, one of the recorded events was observed on two all-sky cameras separated in space. Thus, it is already possible to provide primary statistical data on the MA frequency and their structures registration, similar in spatial and spectral characteristics to SAR arcs observed during the increasing solar activity phase.

Keywords: upper atmosphere, geomagnetic storms, airglow, mid-latitude auroras.

Introduction
At present, quite a lot of midlatitude auroras (MA) studies in different longitude sectors have been conducted, but there is no generally accepted concept of MA in the literature. Numerous articles and monographs (see, for example, [*Chamberlan*, 1961]), devoted to ordinary polar auroras, the midlatitude auroras are devoted to separate sections. A number of authors use the concept "low-latitude aurora", with which they associate auroral emissions observed during magnetospheric storms (MS) at geomagnetic latitudes ≤ 50°. At the same time, other authors use the term "mid-latitude aurora", using as distinguishing features the peculiarities of the mechanisms of mid-latitude emissions amplification during the MS period, the presence of N2+ in the emission spectrum and/or a high ratio of emission intensities [OI] 630.0 and 557.7 nm [*Rassoul et al.*, 1993]. During the periods of large MS, the auroral oval shifts to mid-latitudes synchronously with the movement of the plasmasphere boundary and other boundaries depending on the magnetosphere structure [*Lazutin*, 2015]. At mid-latitudes, powerful MSs are accompanied by a significant intensification of the forbidden line of atomic oxygen [OI] 630.0 nm. This intensity, being a relatively weak component in the mid-latitude luminescence of the upper atmosphere, within a few hours can increase tens of times, transforming into the MA phenomenon. The main dominant MA emission is the atomic oxygen doublet [OI] 630.0-636.4 nm, which may be one of the distinguishing features from the auroras at high latitudes, in which the most intense line is usually the [OI] 557.7 nm emission. This is due to different projections of magnetospheric structures onto the upper atmosphere and ionosphere during a magnetic storm, and, consequently, different energies of the excitation particles and different heights of the auroras airglow.

Stable red auroral (SAR) arcs are rather rarely observed large-scale structures at subauroral and mid-latitudes. A number of highly dynamic processes related to the convection electric field, interaction of trapped energetic particles and thermal plasma occur in the subauroral ionosphere, causing the formation of different types of optical features in this region [*Frey*, 2007]. Interest in SAR arcs has recently been renewed due to the discovery of new optical phenomena such as Strong Thermal Emission Velocity Enhancement (STEVE), "green fence", etc., while interest in other types of MAs during large magnetic storms such as October-November 2003 has been maintained. The interest is intensified with the development of the new solar cycle 25, an increase in the level of geomagnetic activity, and the forecasting of large geomagnetic storms and their optical manifestations in the MAs form.

Optical Instruments
The optical instruments (OI) of the National Heliogeophysical Complex (NHC) include all-sky cameras, Fabry-Perot interferometers, photometers and spectrometers of visible and infrared ranges [*Vasilyev et al.*, 2020]. Two all-sky cameras "KEO Sentry 4" provide registration of the spatial distribution of the main atmospheric lines intensity. The

field of view of the cameras is 180°. The spectral range is selected using an automatic filterwheel. The exposure time for the channels with a narrow spectral range is 55 seconds, and for the broadband OH-channel - 7 seconds. Fabry-Perot interferometers are designed to measure temperature and wind speed at the heights of the main emissions glow of the Earth's upper atmosphere. The visible spectrometer "KEO Spectrograph::VISIBLE" (field of view ~10°, spectral range 400 - 1000 nm, exposure time of one spectral interval is 120 s) and infrared spectrometer "KEO Spectrograph::INFRARED" (field of view ~13°, spectral range 950 - 1650 nm, exposure time of one spectral interval is 20 s). The two-channel photometers "KEO Arges-VF", providing measurement of fast variations of the main emissions of the mid-latitude upper atmosphere, use photomultipliers in the photon counting mode. The field of view can be adjusted from 1° to 10° using a software-controlled input lens. The temporal resolution is 10 ms.

Figure 1 shows the night airglow spectrum in the 400- 900 nm spectral range obtained with the KEO Spectrograph::VISIBLE spectrometer and all-sky camera spectral channels with example frames.

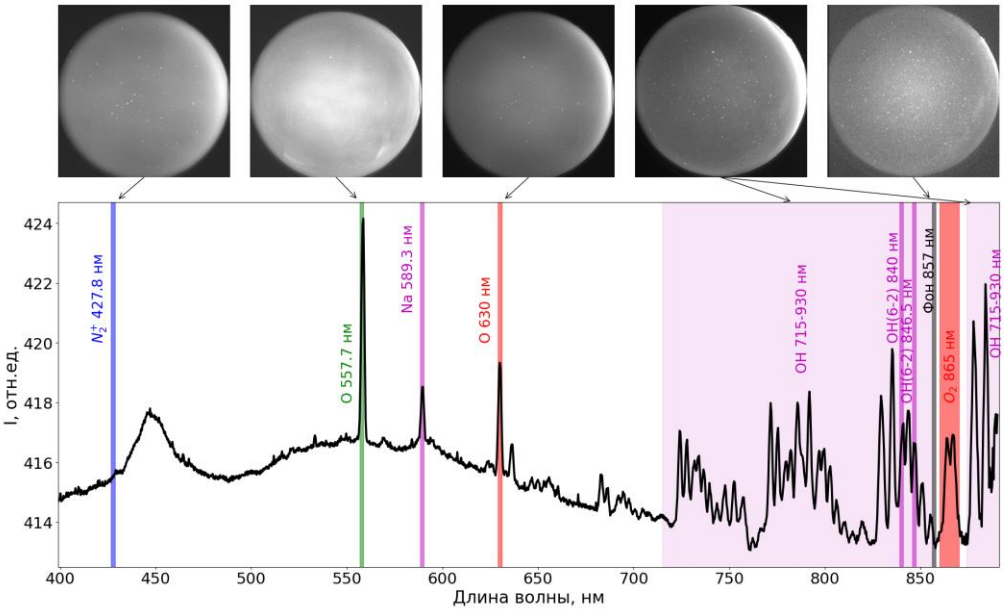

Figure 1. Spectrum of the night sky luminosity in the range 400 - 900 nm (lower panel, averaged spectrum for 23.01.2023), obtained with the KEO Spectrograph::VISIBLE. The spectral channels of the ASI0 and ASI1 all-sky imagers are depicted in color. The upper panel exhibits examples of all-sky imager frames for certain spectral channels (indicated by arrows).

Results

At present, the search for manifestations of geomagnetic activity in the airglow of the upper atmosphere using all-sky camera data is carried out in manual mode. To improve the accuracy and facilitate the work on the detection of disturbances, statistical data on the MAs registration by all-sky cameras depending on the geomagnetic condition were obtained. The Kp and Dst indices were chosen as indicators of geomagnetic perturbation. In addition, attention was paid to the presence of structures similar in spatial characteristics to SAR arcs. On the basis of these data, the threshold geomagnetic indices were obtained, at which the operator in the manual mode on the all-sky cameras frames in the 630 nm channel distinguished MAs, including spatial structures similar by their characteristics to SAR arcs.

Figure 2 shows the obtained distribution of midlatitude auroras visibility (red markers). Further, using the obtained threshold geomagnetic indices, the favorable periods for registration of MAs using the all-sky cameras were estimated. That is, the periods in which the all-sky cameras were in the operational monitoring mode and the previously obtained conditions by geomagnetic indices (Dst<=-25 and Kp>=4.3) were met, but the aurora was not registered (shown by yellow markers in Fig. 2). The auroras absence on the all-sky camera frames for these periods, among others, may be due to the presence of cloud cover or unfavorable observing conditions associated with the Moon's luminosity. We further obtained the seasonal course of the recorded MAs per month (Fig. 3, red curve) and the number of "favorable" periods for the development of MAs (Fig. 3, yellow curve).

Despite the low statistics, the annual dependence shows a tendency towards an increase in the number of auroras in the spring and autumn periods. This corresponds to the Russell-McPherron effect of seasonal variation in geomagnetic activity [*Russell and McPherron*, 1973].

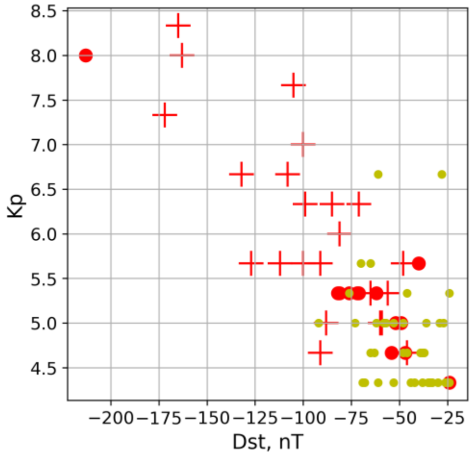

Figure 2. The distribution of recorded MA events as a function of the Dst and Kp indices is shown in the figure on the right (in red). MA with structures similar to SAR arcs are indicated with a plus marker. Yellow markers indicate possibly favorable geomagnetic conditions for MA during the operation of optical instruments (the MA were not registered on the cameras). A total of 34 events were registered, 21 of which had structures similar to SAR arcs. There were 43 "favorable" periods for the MAs occurrence.

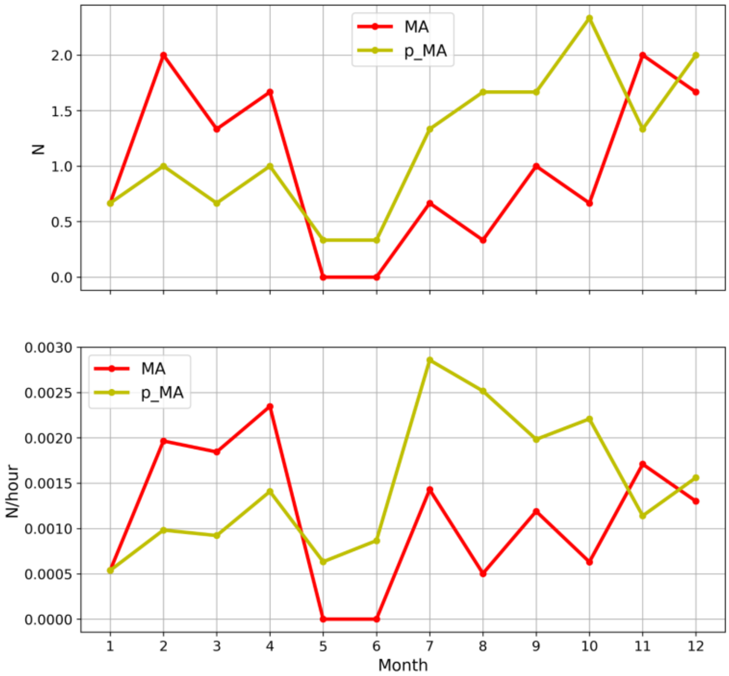

Figure 3. The figure displays the time course of the averaged number of registered MAs per month from 2021 to March, 2024 (in red). The averaged number of "favorable" periods per month for the occurrence of MAs is shown in yellow (upper panel). Averaged time course for 2021-March, 2024 of the number of registered MAs per month in relation to the number of optical observations hours (in red). The average number of favorable periods per month per hour for the occurrence of MAs is shown in yellow (bottom panel).

Conclusion

Midlatitude auroras are a rare geophysical phenomenon [*Krakovetsky et al.*, 2009]. However, according to [*Shiokawa et al.*, 2005], subvisible MAs are observed more frequently. In addition, the observation of SAR arcs in midlatitudes was previously considered to be an extremely rare phenomenon. According to [*Yadav et al.*, 2020], the probability of SAR arcs decreases in Athabasca at subauroral latitudes during higher geomagnetic activity, but at the same time increases at lower latitudes. Moreover, [*Mendillo et al.*, 2016], based on an analysis of 27 years of all-sky camera observations at Millstone Hill (42.6°N, 288.5°E), reported that the frequency of SAR arcs was minimal in solar minimum years and maximal in solar maximum years, in contrast to what is observed at Athabasca (subauroral latitudes). That is, according to [*Yadav et al.*, 2020; *Mendillo et al.*, 2016], one can assume a high probability of registering SAR-arc-type structures during observations at the midlatitude Geophysical Observatory (GPO) of the ISTP SB RAS in the years of high solar activity. During the periods of high activity of the solar cycles 23 and 24, the GPO did not have highly sensitive instruments with good spatial resolution.

The high number of registered MAs in the solar cycle 25 can be related to the high intensity of the solar cycle and is undoubtedly connected with the commissioning of highly sensitive optical instruments of the NHC. OI NHC allow us to detect and record optical manifestations of geophysical and geomagnetic perturbations in the upper atmosphere in the range of geographic latitudes ~46-58 N. The example of multispectral observations in 2021-2024 of MAs and SAR arcs shows the high spatial, temporal and spectral characteristics and efficiency of the optical equipment used. A detailed analysis of individual geomagnetic storms and peculiarities of their optical manifestations is still in progress.

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References

Chamberlan Joseph.W. (1961). Physics of the Aurora and Airglow. *Published by Academic Press Inc.* (London) Ltd. 17, 17 Old Queen Street, London S.W. 1. 704 p.

Frey, H.U. (2007). Localized aurora beyond the auroral oval. *Reviews of Geophysics, 45(1)*, 1003. https://doi.org/10.1029/2005RG000174.

Krakovetsky, Yu.K., Loisha, V.L., Popov, L.R. (1989). Chronologiya polyarnyh siyaniy za poslednee tysyacheletie. *Solnechnye dannye, N. 2.* 110–115. (in Russian).

Lazutin, L.L. (2015). Oval polyarnyh siyanyi - prekrasnaya, no ustarevshaya paradigma. *Solnechno-zemnaya fizika. T. 1, № 1.* P .23-35.

Mendillo, M., Baumgardner, J., Wroten, J. (2016). SAR arcs we have seen: Evidence for variability in stable auroral red arcs. *Journal of Geophysical Research: Space Physics, 121(1)*, 245–262. https://doi.org/10.1002/2015JA021722.

Rassoul, H.K., Rohrbaugh, R.P., Tinsley, B.A., Slater, D.W. (1993). Spectrometric and photometric observations of low-latitude aurorae. *J. Geophys. Res., 98(A5).* 7695–7709.

Russell, C. T., and R. L. McPherron (1973). Semiannual variation of geomagnetic activity. *J. Geophys. Res., 78(1)*, 92–108. https://doi.org/10.1029/JA078i001p00092

Shiokawa, K., Ogawa, T., Kamide, Y. (2005). Low-latitude auroras observed in Japan: 1999–2004. *J. Geophys. Res., 110(A5).* A05202. https://doi.org/10.1029/2004JA010706

Vasilyev, R.V., Artamonov, M.F., Beletsky, A.B., Zorkaltseva, O.S., Komarova, E.S., Medvedeva, I.V., Mikhalev, A.V., Podlesny, S.V., Ratovsky, K.G., Syrenova, T.E., Tashchilin, M.A., Tkachev, I.D. (2020). Scientific goals of optical instruments of the National Heliogeophysical Complex. *Journal Solar-Terrestrial Physics. 6(2)*. 84-97. https://doi.org/10.12737/szf-62202008

Yadav, S., Shiokawa, K., Otsuka, Y., Connors, M. (2022). Statistical study of subauroral arc detachment at Athabasca, Canada: New insights on STEVE. *Journal of Geophysical Research: Space Physics, 127,* e2021JA029856. https://doi.org/10.1029/2021JA029856