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AURORAS DURING EXTREME GEOMAGNETIC STORMS: SOME FEATURES OF MID-LATITUDE AURORA ON FEBRUARY 11, 1958

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Abstract. This paper discusses peculiarities of the great mid-latitude aurora that occurred during the extreme magnetic storm on February 11, 1958. This mid-latitude aurora had unusual optical and spectral characteristics, among which, first of all, were very high (10^5–10^8 R) intensities of atomic oxygen [OI] 630.0 nm emission and an unusually high ratio of the intensities of two forbidden lines of oxygen [OI] 630.0 nm and 557.7 nm ($I_{630}/I_{557.7}$). In some points, this ratio was as high as 10^3–10^4. Analysis of I_{630} dynamics during other extreme geomagnetic storms and associated geophysical conditions and physical processes in Earth's ionosphere and magnetosphere allows us to assume that great mid-latitude auroras are formed during intense substorms in main phases of magnetic storms. In order to interpret the observed features of the February 11, 1958 mid-latitude aurora, we propose to examine the mechanism of level [OI] ^{1}D selective filling in which reactions of resonance recharge of oxygen ions $O^+(^2D)+O\ (^3P)\rightarrow O^+(^4S)+O(^3P,\ ^1D)$ and/or reactions of oxygen atom and molecule collisions with excited components of odd nitrogen can be implemented.

Keywords: mid-latitude aurora, magnetic storms, February 11, 1958 great aurora.

INTRODUCTION

Low- and mid-latitude auroras are extremely rare events usually associated with a strong magnetic storm and earthward coronal mass ejections [Berrilli, Giovannelli, 2022; Knipp et al., 2021]. Auroras with very high visual brightness, which occur exclusively at low and middle latitudes, are attributed to great auroras [Vallance, 1992]. Extreme space weather events that triggered extremely strong magnetic storms such as the events of September 1770, September 1859 (Carrington event), February 1872, May 1921, February 11, 1958, March 1–2, 1989 (Quebec event) were almost always accompanied by intense great auroras at middle and low latitudes. Observations of such auroras have revealed features of their spectral and color characteristics, as well as their morphology and structure — high altitudes of their formation and propagation to low latitudes. Theoretical studies have provided an insight into the unusual spectroscopic characteristics of the mid-latitude auroras, including their bright red color and anomalous vibrational and rotational structure of molecular bands [Vallance, 1992]. Currently, there is no generally accepted definition of the great aurora, and optical parameters of this phenomenon have not been established yet. It is, therefore, necessary to clarify the observed characteristics of individual events to further systematize them.

In this paper, by the example of the February 11, 1958 aurora, an attempt is made to discuss the characteristic parameters of auroras, primarily optical and spectral ones that allow us to attribute mid-latitude auroras to great auroras. The choice of the February 11, 1958 event was due to the abnormally high intensity of auroral [OI] 630.0–636.4 nm atomic oxygen emission. An additional objective is to compare them with characteristics of the recently observed mid-latitude auroras.

OBSERVATIONAL RESULTS

On February 11, 1958, during an extreme magnetic storm (K_p=9, Dst_{min}=–426 nT), a red aurora occurred which was observed in Mexico, North America, the USSR, and Japan [Manring, Pettit, 1959; Akasofu, Chapman, 1962; Yevlashin, 1962; Shuiskaya, 1967; Hikosaka, 1958].

According to [Akasofu and Chapman, 1962], during the February 11, 1958 magnetic storm, as derived from all-sky camera data in North America, Eastern Siberia, and Japan, there were sudden changes in the distribution of auroras. The auroras were observed in bands of varying widths lying parallel to the auroral zone. During the magnetic storm main phase, their northern boundary varied widely simultaneously with the occurrence of magnetospheric substorms.

In the Northern Hemisphere, the aurora was seen up to a geomagnetic latitude of ~40° (L~1.5). According to [Shuiskaya, 1967], the most unusual in the spectral composition of this aurora was the following:

- the ratio of intensities of the two forbidden oxygen lines at 630 nm and 557.7 nm $I_{630}/I_{557.7}$ was as high as 10^3–10^4 at certain moments, whereas in ordinary auroras $I_{630}/I_{557.7}\leq 1$; in high forms of red auroras, $I_{630}/I_{557.7}\leq 10$;
- the presence of a very intense helium line He 1083 nm;
- anomalous vibrational and rotational structure of molecular bands NGN_2^+.

Yevlashin [1962] classified the February 11, 1958 aurora, observed in the auroral zone (station Murmansk), as type A red aurora, noting that it was distinguished for its scales and brightness. Only the initial phase of this aurora was recorded (01:00–05:00 GMT).

Intense auroral activity on February 11, 1958 was detected by photometers at Sacramento Peak (32° N, 105° W, America, New Mexico) and Tonanzintla (Mexico). At Sacramento Peak, the intensity varied from 10^5 to 10^8 R (~300 erg cm^{-2} s^{-1}) for the 630 nm emission and from ~10^3 to 10^4 R for the 557.7 nm emission. The ratio $I_{630}/I_{557.7}$ was about 2.5×10^3 throughout the night [Manring, Pettit, 1959].

Shefov and Yurchenko [1970] reported the results of observation of the February 11, 1958 aurora in Zvenigorod (55° N, 37° E), obtained by photographic methods. The authors, in view of possible errors (up to a factor at least 2–3) attributed to overexposure of photographic material when recording emissions, indicated that the 630 and 557.7 nm emission intensities at certain hours could be 600 kR and 11 kR respectively, which yields $I_{630}/I_{557.7}$~55.

The infrared spectrum covering the range 730.0–870.0 nm [Wallace, 1960] suggests that in the extreme red aurora on February 10/11, 1958 the [OI] 777.4 and 844.6 nm lines were more intense at least five times as compared to the ordinary aurora. The most outstanding feature of the spectrum is the appearance of the forbidden high-intensity ^{2}D—^{2}P multiplet [OII] at 731.9 and 733.0 nm.

At midlatitudes in Asia on February 11, 1958, an exceptionally bright aurora in the form of a huge glow, in the upper part of which there were light pillars, was observed in Irkutsk (52° N, 104 ° E), Blagoveshchensk (50° N, 127° E), and other Russian cities.

DISCUSSION OF OBSERVATIONAL DATA

Dependence of I_{630} on geomagnetic activity

It is generally believed that at midlatitudes the 630 nm emission intensity correlates fairly well with the geomagnetic index *Dst*, which is determined by the ring current, disturbances of the local geomagnetic field at nearby stations, and other near-Earth space parameters [Truttse, 1973; Rassoul et al., 1992; Shefov et al., 2006; Mikhalev, 2019]. For example, Truttse [1973] obtained an empirical ratio for the 630 nm emission intensity of low-latitude red auroras in relation to levels of solar activity characterized by the *F*10.7 index and geomagnetic disturbance described by the *Dst* index,

$$\lg I_{\text{gm}} = (F10.7-160)/50+(|\Phi|-34)\times \times(-Dst)/1460, \quad (1)$$

where I_{gm} is the 630 nm emission intensity in Rayleigh; *F*10.7 is the intensity of solar radio emission at a wavelength of 10.7 cm in sfu (1 sfu=10–22 m^{-2} Hz^{-1}); F is the geomagnetic latitude of the observation station.

During strong disturbances (100≤–*Dst*≤300), the dependence has the form [Truttse, 1973]:

$$\lg I_{\text{gm}} = (1.48\pm0.20)+\left[-Dst/(110\pm10)\right]. \quad (2)$$

A similar dependence of the 630 nm emission intensity on *Dst* was also obtained from mid-latitude observations at the ISTP SB RAS Geophysical Observatory (GPhO) (52° N, 103° E), using, in particular, data on extrastorms on October 30 (K_p=90, $Dst_{\min}$=–383 nT) and November 20, 2003 (K_p=9–, $Dst_{\min}$=–422 nT) [Mikhalev, 2013, 2019]:

$$\lg I_{\text{gm}} = -0.0167\,Dst-4.14. \quad (3)$$

The relationship between the 630.0 nm emission intensity and the *Dst* index has a physical justification. During magnetic storms, the interaction between trapped ring current particles and the outer plasmasphere can produce heat fluxes into the lower thermosphere, causing additional optical radiation in the 630.0 nm emission associated with mid-latitude red aurora [Rassoul et al., 1993].

At the same time, Rassoul et al. [1992] have shown that the temporal variations in the optical radiation of some auroras at low latitudes correlate well with those in the *H* component in magnetograms in the region where the auroras are observed. The maximum optical radiation at midlatitudes occurs simultaneously with the maximum positive deviations of the magnetic field *H* component at nearby stations. Positive deviations of the *H* component at low-latitude observatories during maximum optical radiation correlate with its negative deviations at higher-latitude observatories in the same longitude sector. The authors suggested that the source of the particles that generate auroras at midlatitudes is the ring current. As a result, the following qualitative dependence has been proposed for the mid-latitude emission intensity during geomagnetic disturbances [Rassoul et al., 1992]:

$$I = Dst\,\Delta H, \quad (4)$$

where Δ*H* is the difference between maximum and minimum of the measured horizontal *H* component at the station near the observed emission region on the hourly interval.

The authors note that the *Dst* index is a measure of the total energy of trapped ring current particles, and Δ*H* represents variations in local substorm ionospheric currents generated by large fluxes of low-energy electrons in the thermosphere.

Figure 1 illustrates the behavior of the 630 nm emission intensity during extreme geomagnetic storms, as observed at ISTP SB RAS GPhO, for which there is a tendency for above I_{gm} dependences (1)–(3) on *Dst* to be met.

Figure 2 shows the dynamics of the 630 nm emission intensity compared to the behavior of the *Dst* index during magnetic storms on February 11, 1958 and, for comparison, on March 17, 2015, for which (1)–(3) are not fulfilled. Note that for the March 17, 2015 storm the ratio $I_{630}/I_{557.7}$ was also quite high, sometimes higher than 20.

Data on the 630 nm emission intensity for the February 11, 1958 magnetic storm was acquired by digitizing Figure 3 from [Manring, Pettit, 1959]. The *Dst* index was taken from the database of the World Data Center for Geomagnetism, Kyoto (Japan) [https://wdc.kugi.kyoto-u.ac.jp/dst_realtime/index.html].

For the March 17, 2015 magnetic storm (St. Patrick's storm), the strongest increases in the 630 nm emission intensity were recorded during three activations of the westward electrojet, which developed during enhancement

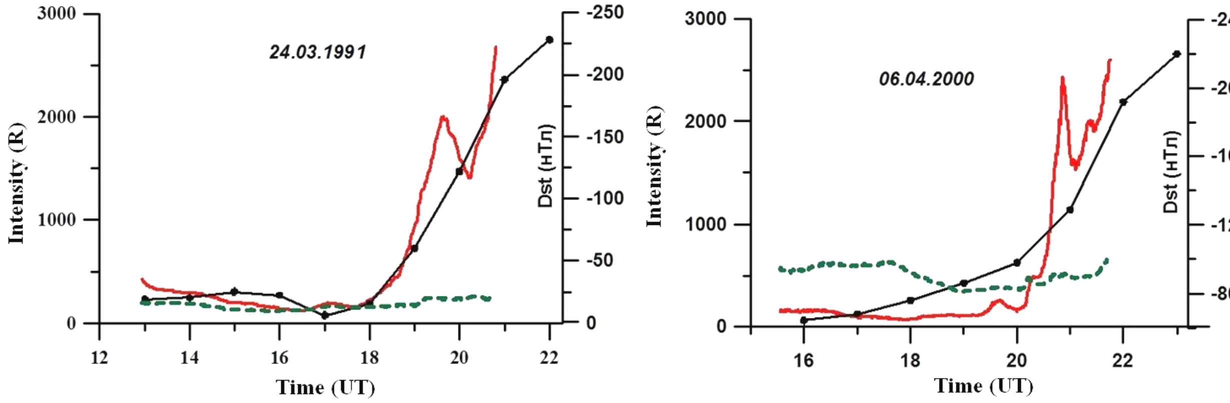

Figure 1. The dynamics of the 630.0 nm [OI] emission intensity (red lines) during the March 24, 1991 and April 6, 2000 magnetic storms, as observed at ISTP SB RAS GPhO, versus the dynamics of the *Dst* index (black lines); green dashed lines indicate the 557.7 nm emission intensity

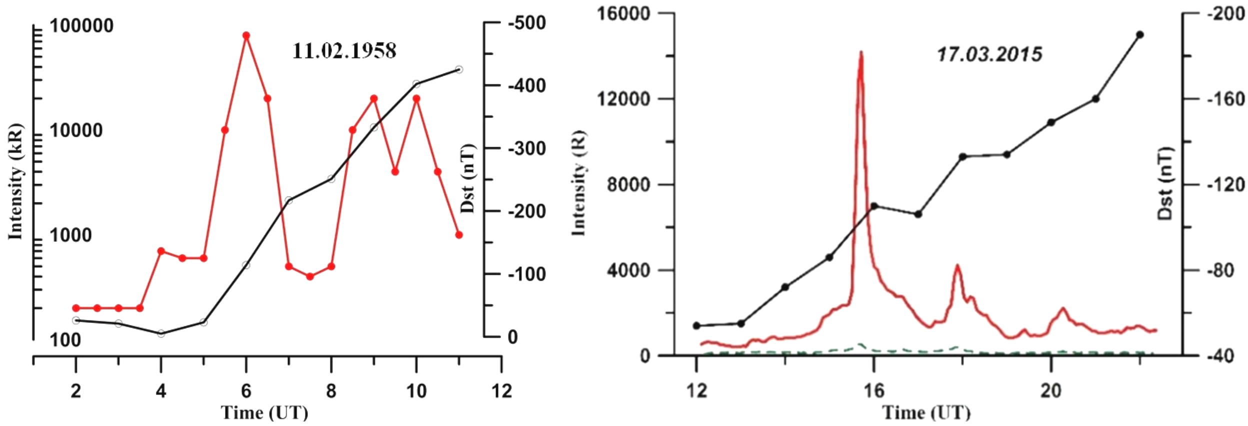

Figure 2. The dynamics of the 630 nm emission intensity (red lines) during the February 11, 1958 magnetic storm at Sacramento Peak (left) [Manring, Pettit, 1959] and St. Patrick's magnetic storm on March 17, 2015 at ISTP SB RAS GPhO (right) versus the dynamics of the *Dst* index (black lines); green dashed line (right) is the 557.7 nm emission intensity

of magnetospheric convection [Zolotukhina et al., 2021].

The high 630 nm emission intensities (~10^5–10^8 R) at midlatitudes during the February 11, 1958 aurora cannot be explained by dependences on *Dst* (1)–(3) since they require unrealistically high *Dst* values practically unobservable in nature. This fact may indicate that local substorm ionospheric and/or magnetospheric current systems (for example, a partial ring current or a substorm current wedge [Sergeev et al., 2011]) are essential in the mechanism of formation of mid-latitude auroras with the dominant 630 nm emission. It is known that changes in the geomagnetic field configuration during magnetospheric storms and substorms alter motion and acceleration of charged particles in the magnetosphere and, in particular, affect the shapes of auroras [Nikolaev, 2015]. Shiokawa et al. [2005], using results of observations made in Japan in 1999–2004, have indicated there is a separate group of mid-latitude auroras generated by substorm activations. In a later paper [Mikhalev, 2019], it is reported that St. Patrick's magnetic storm on March 17, 2015 is also an exception to dependences (1)–(3) discussed above.

Interestingly, Tyasto et al. [2009] when analyzing the September 2–3, 1859 superstorm (the Carrington event), accompanied by intense red auroras at middle and low latitudes, have observed that the nature of variations in the *H* component suggests that during this storm there was a very large amplification of ionospheric and/or magnetospheric current at middle and high latitudes.

The *H*-component variations at the high-latitude station Meanook (61.8° N) on February 11, 1958 [Akasofu, Chapman, 1962] indirectly indicate substorm activations close in time to the enhancement of the 630 nm emission intensity (see Figure 2).

A number of studies have shown that energetic ring current ions can penetrate into the outer plasmasphere at the beginning of the magnetic storm main phase [Fishkova, Martsvaladze, 1985; Dmitriev, Yeh, 2008; Shiokawa et al., 2013] or in the substorm development phase [Ievenko, Greenhouse, 2022].

Relationship of I_{630} with ionospheric parameters. Some features of ionospheric disturbances and magnetospheric oxygen dynamics during severe storms

The review [Danilov, 2013] concludes that during very strong and extreme storms the electron density increases considerably in the upper ionosphere and notes that ionization of the ionosphere by increased fluxes of energetic particles, along with direct penetration of electric fields, contributes to the formation of storm-time increases in ion concentration. Yet, the values of ionospheric disturbances given in this review do not indicate the possibility of selective filling of ^{1}D atomic oxygen levels. The review [Akasofu, 2020] discusses the remarkable discovery in physics of magnetic storms at the end of the last century — ionospheric oxygen ions in the ring current. The oxygen ions are injected from the ionosphere into the magnetotail and are pumped back into the ring current belt. Thus, oxygen ions from the ionosphere are more responsible for the intense ring currents than protons. Before that, it was long believed that only solar wind protons are responsible for the ring current.

Thus, it can be tentatively assumed that the high intensities of all great auroras, or at least some of them, are controlled by intense ionospheric and/or magnetospheric currents that occur during substorms due to a significant increase in the partial ring current or the substorm current wedge. On the contrary, the intensity of auroras during large geomagnetic storms, shown in Figure 1, is due to an increase in the symmetric ring current. The dynamics of the [OI] 630 nm emission during certain strong and extreme auroras is likely to exhibit signs of manifestation of all the magnetospheric current subsystems considered.

The disappearance of the direct dependence of the [OI] 630 nm emission intensity on the *Dst* index in the storms similar to the February 11, 1958 and March 17, 2015 storms may also be associated with the method of determining the *Dst* index (for four longitudinally spaced stations) and with the longitude asymmetry in the magnetic response of the *H* component to magnetospheric storms in the daytime (negative) and nighttime (positive) sectors of the mid-latitude magnetosphere [Saiz et al., 2021]. Saiz et al. [2021] note that the greatest asymmetry takes place in the magnetic storm main phase (during the most intense red mid-latitude auroras) and is recorded in narrow local time sectors.

The very large ratio $I_{630}/I_{557.7}$ (~10^3–10^4), recorded in the February 11, 1958 aurora, casts doubt on the heating of the thermosphere [Danilov, 2013] during magnetic storms as the main cause of the abnormally high intensity of the [OI] 630 nm emission.

It is generally believed (see, e.g., [Akasofu, 1989]) that the increase in the 630 nm emission intensity at midlatitudes during geomagnetic storms is explained by the excitation of oxygen atoms by heated electrons during direct collisions in the reaction [Shefov et al., 2006; Dashkevich, Ivanov, 2022]:

$$\mathrm{O}\left({}^3\mathrm{P}\right)+\mathrm{e}\rightarrow\mathrm{O}\left({}^1\mathrm{D}\right)+\mathrm{e}. \tag{5}$$

However (see Figure 2), according to [Rees, Luckey, 1974], the ratio $I_{630}/I_{557.7}$ in collisions with electrons having the Maxwell distribution function with characteristic energies ~0.3–10 keV does not exceed 10 at altitudes 340–350 km. Calculations of the [OI] 630 and 557.7 nm emission, presented in [Rassoul et al., 1993], also show that red auroras with $I_{630}/I_{557.7}$~4 require electrons with energies ~0.01–10 keV.

These facts make it reasonable to search for other mechanisms of quasi-selective filling of oxygen atom levels ^{1}D at F2-region heights and/or inflow of additional portions of oxygen from the plasmasphere or magnetosphere.

Rassoul et al. [1993] provides a nomenclature of several types of low- and mid-latitude auroras, among which two types are of interest to us: 1) type d associated with the excitation of the dominant 630 nm emission by electrons with ~10–1000 eV energies (with $I_{630}/I_{557.7}$~1–10); 2) HP auroras (Heavy Particle aurora) caused by heavy particles with ~1–100 keV energies and linked to the precipitation of neutral atoms and ions. At the same time, the dominant emission for HP auroras is only the radiation of the first negative system $1N_2^+$. The type d mid-latitude auroras may include the auroras shown in Figure 1 of this work.

Possible mechanisms and reactions of selective enhancement of I_{630} in mid-latitude auroras

For HP auroras, one of the possible reactions contributing to the selective filling of the O(^{1}D) level is given in [Mahadevan, Roach, 1968; Solomon et al., 1988]:

$$\mathrm{O}^+\left({}^2\mathrm{D}\right)+\mathrm{O}\left({}^3\mathrm{P}\right)\rightarrow\mathrm{O}^+\left({}^4\mathrm{S}\right)+\mathrm{O}\left({}^3\mathrm{P},\,{}^1\mathrm{D}\right). \tag{6}$$

This reaction is a reaction of resonant charge exchange of oxygen ions on oxygen atoms to produce an excited O* atom in the state ^{1}D. The authors note that the yield of O(^{1}D) in reaction (6) is unknown, but likely to be insignificant, except for very high (~400 km) altitudes.

Dashkevich and Ivanov [2022] for altitudes 100–300 km have examined the known potential sources of excitation of the ^{1}D atomic oxygen therm in auroras among which reactions with excited components of odd nitrogen may be of interest to us:

$$\mathrm{N}\left({}^2\mathrm{D}\right)+\mathrm{O}_2\rightarrow\mathrm{NO}+\mathrm{O}\left({}^3\mathrm{P},\,{}^1\mathrm{D}\right), \tag{7}$$

$$\mathrm{N}\left({}^2\mathrm{D}\right)+\mathrm{O}\left({}^3\mathrm{P}\right)\rightarrow\mathrm{N}\left({}^4\mathrm{S}\right)+\mathrm{O}\left({}^3\mathrm{P},\,{}^1\mathrm{D}\right). \tag{8}$$

For these reactions, the ^{1}D therm is also selectively filled with respect to ^{1}S.

Gogosheva [1979] has shown that during magnetically disturbed periods reaction (8) can provide almost half of the observed [OI] 630 nm emission intensity. Dissociative recombination NO^+ + e → N(^{2}D) + O(^{3}P) at night is the main source of nitrogen in the metastable state N(^{2}D), which can be a fairly effective source of excited O(^{1}D) atoms. Moreover, the metastable state N(^{2}D) is the upper level of the transition to the ground state at which an atomic nitrogen doublet 519.99–520.23 nm is emitted (520 nm emission). At midlatitudes under quiet geomagnetic conditions, the 520 nm emission intensity is quite low: ~0.5–3 R. For a number of geomagnetic storms, the 520 nm emission can significantly increase [Tinsley et al., 1986; Mikhalev et al., 2018] (see Figure 3), which may indicate an increase in the filling of the N(^{2}D) level and hence the oxygen yield O(^{3}P, ^{1}D) in reactions (7)–(8). For example, noteworthy is the reaction that is the main source of NO^+ at night in the F-region of the ionosphere:

$$\mathrm{O}^+ + \mathrm{N}_2\rightarrow\mathrm{NO}^+ + \mathrm{N}. \tag{9}$$

According to [Gogosheva, 1979], the coefficient of this reaction depends on the oscillatory temperature N_2 and increases by an order of magnitude when the temperature rises to 3000 K.

Oxygen atoms and ions are the same in the left parts of Equations (6) and (8), (9). It would be appropriate to recall the results of the February 10/11, 1958 aurora spectrometry obtained in [Wallace, 1960]. The spectra exhibited an abnormal increase in the [OI] 777.4 and 844.6 nm atomic oxygen emission intensities as compared to ordinary auroras and the occurrence of intense [OII] 731.9 and 733.0 nm oxygen ion emissions atypical for ordinary auroras. The [OII] 731.9 and 733.0 nm emissions, with some degree of confidence (against the background of the OH hydroxyl band (8-3)), can also be found in the March 17, 2015 mid-latitude aurora. Figure 3 shows fragments of the spectrum in wavelength ranges 500–600 [Mikhalev et al., 2018] and 700–760 nm, recorded during the March 17, 2015 magnetic storm by the Shamrock spectrograph SR-303I.

Thus, we can single out some characteristics of the February 11, 1958 and March 17, 2015 mid-latitude auroras: high values of the [OI] 630 nm intensities with a poorly developed ring current, which cause the absence of dependence on the *Dst* index; similarity in the overall dynamics of the 630 nm emission intensity, correlating with substorm activations and substorms; the high ratio $I_{630}/I_{557.7}$; the presence of spectral lines of atoms and oxygen ions. The difference between the compared storms lies in the quantification of these characteristics.

Mention should be made of two more features of great auroras — a large latitudinal extent and the appearance of light pillars against an intense red background [Kataoka et al., 2019]. The large latitudinal extent of the auroras can be provided by the cascade reaction of charge exchange of heavy particles when ring current ions with energies of tens of keV with an initial isotropic pitch-angle distribution are lost in the charge exchange processes in collisions with atoms of the upper atmosphere (outer plasmasphere). In this case, energetic neutrals with energies of tens of keV are formed which are not controlled by a magnetic field and precipitate into the thermosphere, entering into numerous charge exchange reactions there. Light pillars require special consideration. Types of large-scale solar wind structures that lead to differences in the dynamics of magnetic storms (see, e.g., [Dremukhina et al., 2020]) and hence in the characteristics of extreme auroras also call for further investigation.

SUMMARY AND CONCLUSIONS

Taking into account the important role of magnetospheric-ionospheric current systems in forming geomagnetic storms and substorms, as well as optical and spectral features of the February 11, 1958 mid-latitude aurora, we can preliminarily formulate some conditions for the formation and signs of great auroras.

1. High intensities of great auroras with the dominant [OI] 630 nm emission, or at least some of them, are observed during intense substorms and are probably related to the formation of local ionospheric-magnetospheric current systems. This is their difference from the mid-latitude auroras observed during extreme global magnetic storms, characterized by the dependence on the symmetric ring current and hence on the *Dst* index.

2. The existence of the longitude asymmetry in the magnetic response of the *H* component to magnetospheric substorms, which is caused by the formation of a system of ionospheric-magnetospheric currents in narrow local time sectors, suggests that great auroras occur in a limited longitude sector during magnetic storm main phases.

3. The high ratio of the atomic oxygen emission intensities $I_{630}/I_{557.7}$~10^3–10^4 may indicate a mechanism of selective filling of the [OI] ^{1}D level, where, in particular, reactions of resonant charge exchange of ring current oxygen ions to produce an excited [OI] ^{1}D atom and/or reactions of collisions of oxygen atoms and molecules with excited odd nitrogen components can take place.

4. Intense spectral lines of [OI] 777.4 and 844.6 nm atoms and [OII] 731.9 and 733.0 nm oxygen ions can be observed in great-aurora spectra.

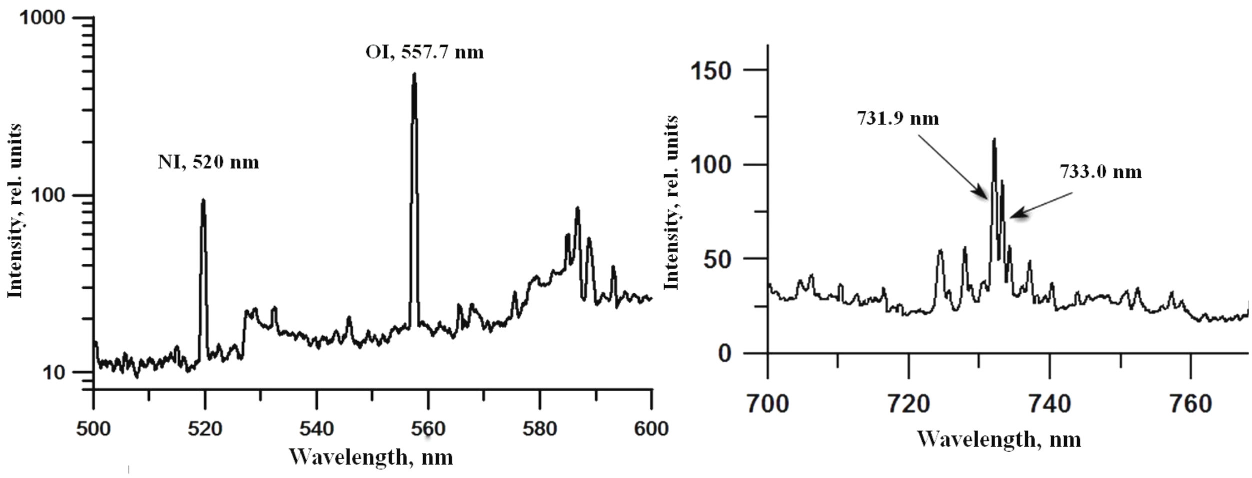

Figure 3. Fragments of the spectrum in ranges 500–600 nm [Mikhalev et al., 2018] and 700–760 nm recorded during the March 17, 2015 magnetic storm by the Shamrock spectrograph SR-303I

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