Solar-Terrestrial Physics. 2020. Vol. 6. Iss. 3. P. 81–85. DOI: 10.12737/stp-63202011. © 2020 A.V. Mikhalev. Published by INFRA-M Academic Publishing House
Original Russian version: A.V. Mikhalev, published in Solnechno-zemnaya fizika. 2020. Vol. 6. Iss. 3. P. 99–104. DOI: 10.12737/szf-63202011. © 2020 INFRA-M Academic Publishing House (Nauchno-Izdatelskii Tsentr INFRA-M)

MANIFESTATION OF SOLAR ACTIVITY AND DYNAMICS OF THE ATMOSPHERE IN VARIATIONS OF 577.7 AND 630.0 nm ATMOSPHERIC EMISSIONS IN SOLAR CYCLE 24

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Abstract. In the paper, variations of the night emission intensities in the 557.7 and 630 nm atomic oxygen lines [OI] in 2011–2019 have been analyzed. The analysis is based on data from the ISTP SB RAS Geophysical Observatory. The emission intensities are compared with atmospheric, solar, and geophysical parameters. High correlation coefficients between monthly average and annual average 630.0 nm emission intensities and solar activity indices F10.7 have been obtained. This suggests a key role of solar activity in variations of this emission in the period of interest. Variations of the 557.7 nm emission demonstrate to a greater extent the correlations of the stratospheric zonal wind (QBO.U30 index) with quasi-biennial oscillations. The causes of the weak dependence of the 557.7 nm emission intensity on solar activity in solar cycle 24 are discussed.

Keywords: upper atmosphere, 557.7 and 630.0 nm emissions, solar activity.

INTRODUCTION

The first studies of interannual and long-term variations in night sky mid-latitude emissions are dated back to the 1920/30s [Lord Rayleigh, Spencer Jones, 1935]. The most comprehensive data on long-term variations in upper atmosphere emissions spanning about six solar cycles (solar cycles 18–23) was obtained in the later half of the 20th century — the earlier half of the 21st century (see, e.g., [Fukuyama, 1977]). It is now an established fact that long-term variations of night sky emission intensities in the 557.7 and 630 nm atomic oxygen lines (85–115 and 180–250 km emission heights respectively) depend on the level of solar activity.

The dependence of 630 and 557.7 nm emission intensities on solar activity is also reliably observed at high latitudes (see, e.g., results of long-term observations on the meridian of Yakutsk in [Ievenko et al., 2011, 2019]). It should be noted here that the degree of manifestation of solar activity effects in these emissions in different solar cycles may differ [Givishvili et al., 1996; Mikhalev, Medvedeva, 2009].

The 557.7 nm emission heights are affected both by the dynamics of underlying atmospheric layers and by solar activity. Identification and separation of the effects, caused by the dynamics of the underlying atmosphere and solar activity, are difficult and, to our opinion, still unsolved problems. Probably for this reason, results for different stations and observation periods show a varying degree of dependence of the 557.7 nm emission intensity on solar activity: from very high [Fukuyama, 1977] to moderate [Fishkova et al., 2000] and low — or even its absence [Midya et al., 2002].

The 630.0 nm emission is more sensitive to solar activity due first to a greater height of its emission (the ionospheric F-region) and second to formation mechanisms. At middle latitudes, this emission is excited by dissociative recombination, photodissociation, and collisions with photoelectrons. The ratio of contributions of these mechanisms to the total 630 nm emission intensity depends on latitude, longitude, local time, and season [Shefov et al., 2006]; therefore the 630.0 nm emission intensity dependence on solar activity may be complex and have its features in different longitude-latitude zones.

In this paper, on the basis of experimental data obtained at the ISTP SB RAS Geophysical Observatory (GPhO) (52° N, 103° E) in 2011–2019, a preliminary analysis of solar-activity-dependent variations of night sky emission intensities in the 557.7 and 630.0 nm atomic oxygen lines in solar cycle 24 for middle latitudes of Asia is carried out.

EQUIPMENT AND OBSERVATIONAL METHOD

This work is based on observations of 577.7 and 630.0 nm atomic oxygen emissions obtained at ISTP SB RAS GPhO with a patrol spectrometer SATI-1M, designed to study intensity variations of the main night sky emissions (OI 557.7 and 630.0 nm, NaI 589.0–589.6 nm, etc.) during heliogeophysical disturbances of different nature. The spectrometer is oriented to the north with the optical axis elevated at an angle of ~23° above the horizon. The vertical angular field of view is ~25°, the exposure time is 260 s. The main characteristics of the spectrometer SATI-1M are available at [http://atmos.iszf.irk.ru/ru/data/spectr]. The relative emission intensities obtained were reduced to absolute zenith values (for more detail, see [Mikhalev, 2018]).

It is common knowledge that the 630.0 nm emission intensity over night falls from ~200–300 R during the dusk to ~30–50 R around midnight, then changes slightly until the local dawn or until the predawn enhancement associated with the beginning of dawn in the magnetically conjugate ionosphere [Fishkova, 1983]. This is due to the presence of several mechanisms behind the

630.0 nm emission excitation whose contribution depends on the time of day and heliogeophysical conditions [Toroshelidze, 1991]. In this regard, this paper analyzes 630 nm emission variations from near-midnight values (23–01 LT). The analysis of 557.7 nm emission variations is based on mean nighttime values.

In this work, data is used for the period from September 2011 to December 2019, covering the growth, maximum, and decline phases of solar cycle 24. Observations in 2011 were made at night for one–two weeks, close to the new moon; since April 2012, every day in automatic mode. The method for detecting spectral lines in the patrol spectrometer SATI-1M involves recording the varying background emission near a spectral line under study. In this regard, the observational data acquired at clear and relatively clear nights, generally in moonless intervals, has been used for the analysis. The nights during which severe geomagnetic storms occurred were excluded from consideration.

OBSERVATIONAL RESULTS AND DISCUSSION

The 630.0 nm emission

Figure 1 shows variations in monthly average values of the $F10.7$ index, which characterizes the solar radio emission flux at a wavelength of 10.7 cm and is used to estimate the level of solar activity; the geomagnetic activity index A_p, and the emission intensity in the 630 nm atomic oxygen line I_{630}. To smooth short-term oscillations and to identify the main trends or cycles, moving averages have been utilized.

For the data presented in Figure 1, correlation coefficients were: ~ 0.81 (N=87) between $F10.7$ and I_{630}, ~0.195 (N= 87) between A_p and I_{630}; N is the number of values in the samples. Hereafter, one-dimensional correlation coefficients with confidence probabilities of 0.95 and a one-dimensional linear regression are applied. Figure 2 shows variations of annual average 630.0 nm emission intensity and $F10.7$, and dependence of annual average I_{630} on solar activity ($F10.7$) in 2012–2019. The period of interest covers growth, maximum, and decay phases of solar cycle 24.

For the data presented in Figure 2, the correlation coefficient between $F10.7$ and I_{630} is ~0.85. For annual values of $F10.7$ and I_{630}, the coefficient of determination is ~0.72, indicating a decisive role of solar activity in interannual variations of this emission in solar cycle 24.

Using data on long-term variations of annual average 630 nm emission intensities in 1958–1992 (solar cycles 19–22) [Givishvili et al., 1996], Shefov et al. [2006] have obtained a correlation dependence for midnight intensities (empirical model)

$$\Delta I_F = (0.0060 \pm 0.0015)(F10.7 - 130), \qquad (1)$$

where ΔI_F is the 630 nm emission intensity variation relative to the mean value depending on the level of solar activity from $F10.7$ [10^{-22} W/m^2 Hz].

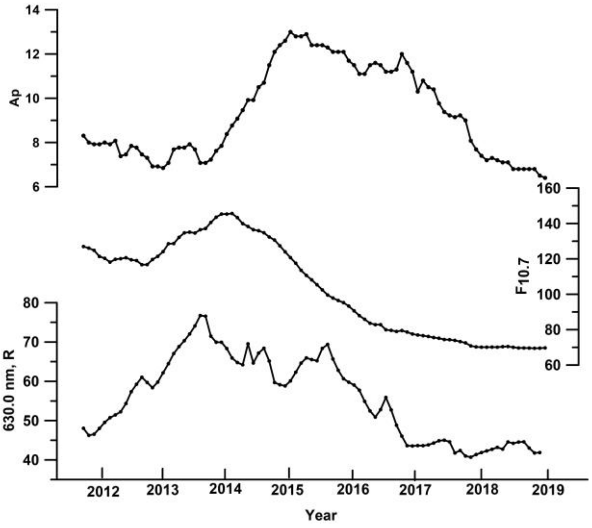

Figure 1. Variations of monthly average 630.0 nm emission intensities (I_{630}, lower curve) and $F10.7$ (middle curve) and A_p (upper curve) indices. Moving averages over 13 months

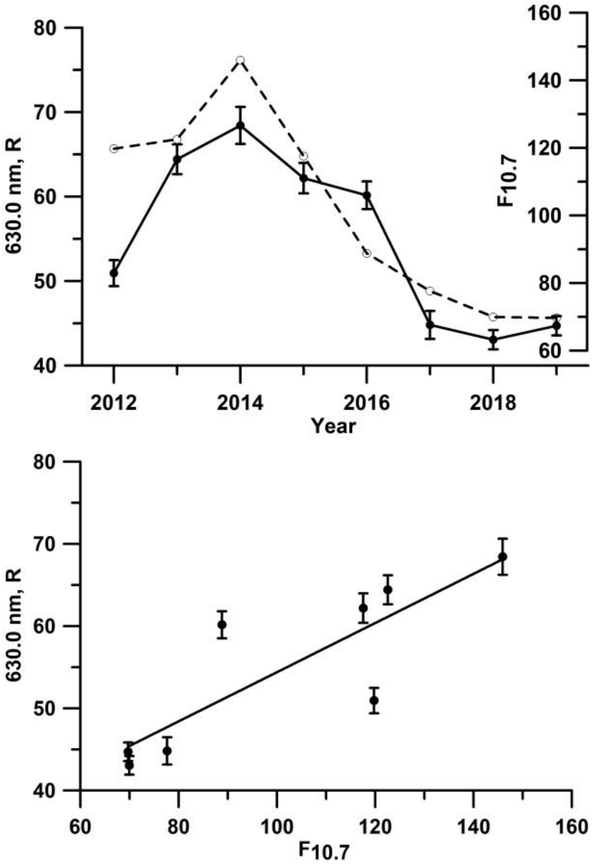

Figure 2. Variations of annual average values (*a*) of the 630.0 nm emission intensity (dark circles, solid line) and $F10.7$ index (open circles, dashed line). Annual average 630.0 nm emission intensities as a function of $F10.7$ (*b*). For I_{630}, standard errors of the mean are given

To compare the I_{630} dependence on $F10.7$ from the empirical model, represented by expression (1), with the I_{630} data presented in this work, it is more convenient to use the I_{630} values normalized to the means. This eliminates the trend and the dependence of emission intensity on latitude, longitude, and other parameters [Shefov et al., 2006]. In this case, the use of annual average $F10.7$ for solar cycle 24 in (1) yields the following dependence of the 630.0 nm emission intensity on $F10.7$:

$$I_{630} = (0.0060 \pm 0.0015)F10.7 + 0.22. \quad (2)$$

Expression (2) is derived through a simple transformation of (1): $I_{630}=1+\Delta I_F$.

For the 630.0 nm emission intensities actually observed in solar cycle 24, the following dependence on $F10.7$ has been obtained:

$$I_{630} = (0.005 \pm 0.0038)F10.7+0.45. \quad (3)$$

Expression (3) has been derived from the I_{630} data presented in Figure 2, normalized to the mean I_{630}~54.8 over the period of interest.

Figure 3 shows the $F10.7$ dependences of relative 630.0 nm emission intensities derived from expressions (2) (open circles, dashed line) and (3) (filled circles, solid line). For most annual average I_{630} values observed in solar cycle 24 (Figure 3), there is a fairly good agreement with the empirical model [Shefov et al., 2006], which probably indicates the preservation of the basic mechanisms behind the relationship between the 630.0 nm emission and solar activity over the last few solar cycles. The largest deviations (the cause of which is not clear yet) of the observed I_{630} values from those obtained by the empirical model have been recorded only in two years (2012 and 2016). This might have been due to the influence of the global circulation of the underlying atmosphere, discussed in more detail below in terms of the 557.7 nm emission. This is supported by a relatively high, statistically significant correlation coefficient of ~0.41 between monthly moving averages of I_{630} over 13 months and of the index of quasi-biennial oscillations of the equatorial stratospheric zonal wind https://en.wikipedia.org/wiki/Stratosphere. It is appropriate to note that we also observed the 630.0 nm emission intensity variations with a period of two to three years in the previous solar cycle [Mikhalev et al., 2008a], but they were, in our opinion, linked to cyclic aperiodic solar activity variations [Shefov et al., 2006].

The ratio between annual average 630 nm emission intensities at maximum and minimum of solar cycle 24 (I_{2014}/I_{2018}) is ~1.6, which is somewhat lower than those for mid-latitude stations in previous solar cycles: ~ 2 — Upper Provence [Barbier, 1965], ~ 2.5 — Zvenigorod [Truttse, Belyavskaya, 1975], ~2.3 — Irkutsk [Mikhalev et al., 2008a]. Nonetheless, this value agrees fairly well with the value of ~1.7 found from Formula (1) of the empirical model [Shefov et al., 2006], accounting for current annual average $F10.7$ for 2012–2019. The resulting low value of the annual average 630 nm emission intensity variations might reflect such a feature of solar cycle 24 as minor variations of solar activity from maximum to minimum, as compared to previous cycles.

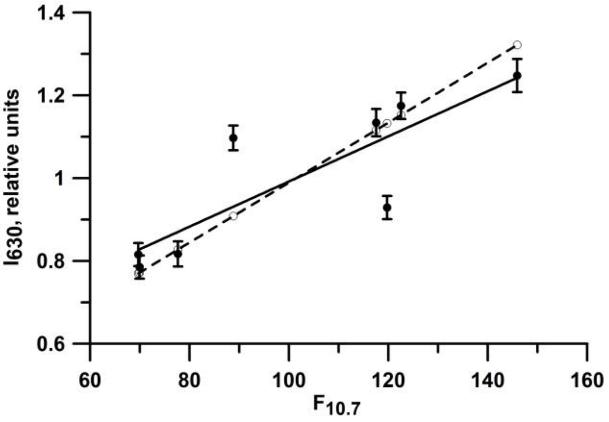

Figure 3. Annual average 630.0 nm emission intensities as a function of $F10.7$ for solar cycle 24, as derived from the empirical model [Shefov et al., 2006] (expression (2), open circles, dashed line) and from GPhO observational data (expression (3), filled circles, solid line). For the I_{630} values obtained from GPhO data, standard errors of the mean are given

The 557.7 nm emission

Many papers dealing with the 557.7 nm emission intensity ($I_{557.7}$) dependence on solar activity indicate a positive correlation between $I_{557.7}$ and $F10.7$ [Fukuyama, 1977; Givishvili et al., 1996; Fishkova et al., 2000]. Individual studies for some observation intervals and solar cycles note a negative or variable correlation between these parameters [Midya et al., 2002; Mikhalev et al., 2008a; Mikhalev et al., 2008b; Mikhalev, Medvedeva, 2009]. As has been mentioned in Introduction, the 557.7 nm emission behavior can be affected by the underlying atmosphere, in particular by Quasi-Biennial Oscillations (QBO) of the equatorial stratospheric zonal wind https://en.wikipedia.org/wiki/Stratosphere [Fukuyama, 1977; Uma Das et al., 2011]. The possible influence of the global atmospheric circulation on $I_{557.7}$ during El Niño/La Niña has been discussed in [Mikhalev, 2017].

Figure 4 shows variations of monthly average 557.7 nm emission intensities, $F10.7$, and QBO of the stratospheric zonal wind *QBO.U30* [https://www.cpc.ncep.noaa.gov/data/indices/qbo.u30.index], as well as the *ONI* index linked to the El Niño/La Niña phenomenon [https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/enso-stuff/ONI_v5.php]. According to the data presented in Figure 4, a statistically significant correlation between $I_{557.7}$ and $F10.7$, $I_{557.7}$ and *ONI* has not

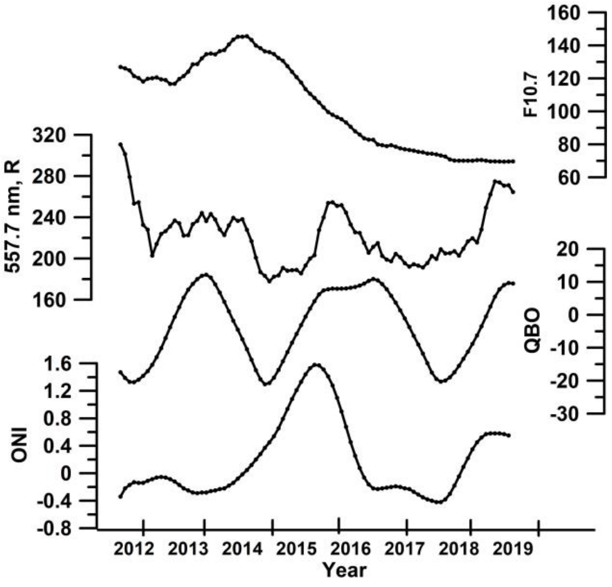

Figure 4. Variations of monthly average 557.7 nm emission intensity, $F10.7$, *QBO.U30*, and *ONI*. Moving averages over 13 months

been obtained. The correlation coefficients between *QBO.U30* and $I_{557.7}$ were ~0.26 (N=88, the entire observation period) and ~0.6 (N=78, 2013–2019). These correlation coefficients are statistically significant.

The analysis of Figure 4 and estimated correlation coefficients between the values analyzed show that the 557.7 nm emission variations in solar cycle 24 might have been most strongly affected by features of the dynamics and global circulation of the atmosphere, linked in particular to QBO of the stratospheric zonal wind. However, we should not rule out the El Niño/La Niña effect. This assumption is confirmed by the work [Sun et al., 2018], in which the authors demonstrate the long-term effect of El Niño/La Niña on tidal QBO in the mesosphere and lower thermosphere. This calls for further studies of possible El Niño/La Niña effects in variations of characteristics of upper atmosphere emissions.

Possible influence of the dynamics of the underlying atmosphere, including the stratosphere and the troposphere, on 557.7 emission intensity variations has been discussed in a number of studies (see, e.g., [Fukuyama, 1977; Wang et al., 2002]). Note that the global distribution of $I_{557.7}$ has pronounced latitude-longitude structures and dependences. The longitude dependence of $I_{557.7}$ has been discovered relatively recently and is attributed to quasistationary planetary waves [Wang et al., 2002], whose penetration into the upper atmosphere is determined by atmospheric circulation features. In this case, we can assume that the variations of latitude-longitude 557.7 nm emission structures driven by features of the global circulation can lead to $I_{557.7}$ variations in certain latitude-longitude zones. Of particular interest are the results received in [Shefov, 1985], in which for upper atmosphere emissions the mean planetary solar energy absorbed at a height of ~100 km was compared with the energy of orographic disturbances, which were generated in the troposphere as internal gravity waves and propagated to the upper atmosphere. According to [Shefov, 1985], these values are comparable, and hence the influence of the lower atmosphere circulation may be akin to the solar activity effect.

Influence of solar activity on 557.7 nm emission intensity variations at large time scales (about one year or more) is estimated at 20–30 % [Fishkova, 1983; Uma Das et al., 2011]. The correlation coefficient between annual average $I_{557.7}$ and F 10.7 according to long-term data (1957–1992) in [Fishkova et al., 2001] is positive and is ~0.36 ± 0.16. Within the solar cycle, for annual average $I_{557.7}$ these variations generally prevail. This paper has not revealed a significant effect of solar activity on 557.7 nm emission intensity variations in solar cycle 24, while the dominant $I_{557.7}$ variations largely correlate with the *QBO.U30* and *ONI* indices. In this regard, the paper by Midya et al. [2002] should be mentioned in which for 1984–1985 (solar minimum between cycles 21 and 22) a negative correlation between monthly average $I_{557.7}$ and F10.7 (the correlation coefficients of –0.46 and –0.15 respectively are not statistically significant) has been observed; whereas for 1987, a positive correlation. We have also obtained time intervals with negative and positive correlations between monthly average $I_{557.7}$ and F10.7 from GPhO observations in solar cycle 23 [Mikhalev et al., 2008a].

CONCLUSIONS

For solar cycle 24, relatively high correlation coefficients between monthly and annual average values of the 630.0 nm emission intensity and the solar activity index F10.7 (~0.77 and ~0.81 respectively) have been obtained. This demonstrates a decisive role of solar activity in variations of this emission in solar cycle 24 on the time scales considered. The resulting correlation dependence of the 630.0 nm emission intensity on F10.7 agrees reasonably well with the empirical model [Shefov et al., 2006], constructed from observations in solar cycles 19–22 (1958–1992), which may suggest the preservation of the basic physical mechanisms behind the relationship between the 630.0 nm emission and solar activity over the last few solar cycles. A low ratio of extreme annual average 630 nm emission values corresponding to solar maximum and minimum is observed which is due to the low level of solar activity in cycle 24.

For the 557.7 nm emission intensity, no statistically significant correlation between F10.7 and $I_{557.7}$ in the analyzed time interval has been detected. The 557.7 nm emission variations largely correlate with quasi-biennial oscillations of the stratospheric zonal wind (the *QBO.U30* index). This is likely due to the combination of the lower altitude location of the 557.7 nm emission layer (with respect to the 630.0 nm emission layer) and the abnormally low level of solar activity in current solar cycle 24, which might have led to the predominance of the effects of the underlying atmosphere over solar activity effects.

The work was performed with budgetary funding of Basic Research program II.16. This work is based on data obtained using the equipment of Center for Common Use «Angara» [http://ckp-rf.ru/ckp/3056, http://ckp-angara.iszf.irk.ru].

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How to cite this article

Mikhalev A.V. Manifestation of solar activity and dynamics of the atmosphere in variations of 577.7 and 630.0 nm atmospheric emissions in solar cycle 24. *Solar-Terrestrial Physics*. 2020. Vol. 6. Iss. 3. P. 81–85. DOI: 10.12737/stp-63202011.