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ESTIMATING THE AVERAGE ENERGY OF AURORAL ELECTRONS FROM 427.8 nm EMISSION INTENSITY MEASUREMENTS

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Abstract. We propose a method for estimating average energy of precipitating electrons from 427.8 nm emission intensity measurements. This method is based on the experimental dependence of the ratio of λ630.0 and λ427.8 nm emission intensities on the λ427.8 emission intensity and modeling calculations of the dependence of the average auroral electron energy on the $I_{630.0}/I_{427.8}$ ratio. We present numerical estimates of the influence of three factors on this dependence: the shape of the auroral electron energy spectrum, the atomic oxygen concentration, and the NO concentration. The dependence of the average energy of the auroral electron flux on the 427.8 nm emission intensity is obtained and its analytical approximation is presented.

Keywords: auroras, diagnostics, average energy, electron precipitation, emission intensity, 427.8 nm, 630.0 nm.

INTRODUCTION

Estimating auroral electron flux parameters from spectrophotometric observations is one of the urgent problems in diagnostics of ionospheric plasma conditions during auroras. The traditional approach is based on the study of the dependence of the ratio between intensities of two emissions on the average energy of auroral electrons E_{aver}; the selected emissions should have different rates of quenching in various depths of electron penetration into the atmosphere. When using ground-based observations, the λ630.0 and λ427.8 nm emission intensity ratio is generally examined. The λ630.0 nm emission occurs due to the radiation transition $O(^1D \rightarrow {}^3P)$. Since the ^1D state of atomic oxygen is metastable with ~110 s lifetime, it is subjected to quenching whose rate increases with increasing depth of auroral electron penetration into the atmosphere. The λ427.8 nm emission is one of the bands of the first negative system 1NG N_2^+, resulting from the transition $B^2\sum_u^+ \rightarrow X^2\sum_g^+$. This transition is optically resolved. The lifetime of the ion in the $B^2\sum_u^+$ state is ~10^{-8} s; therefore, we can neglect collisional deactivation and assume that this state is completely deactivated due to radiation transitions. Thus, we can expect that the λ630.0 and λ427.8 nm emission intensity ratio depends on E_{aver}. This ratio was first used to estimate the average energy of auroral electrons in [Rees, Luckey, 1974], in which the dependences of $I_{630.0}/I_{427.8}$ on $I_{427.8}$ were calculated for various characteristic energies of precipitating electrons having a Maxwellian energy spectrum. By analogy with [Rees, Luckey, 1974] in [Germany et al., 1990; Dashkevich et al., 1993], to estimate the average energy of auroral electrons from satellite measurements of auroral intensity in the extreme ultraviolet spectral region, the emission intensity ratios of two LBH bands with different degrees of absorption in the Schumann—Runge O_2 continuum were proposed.

The purpose of this work is to explore the possibilities of estimating the average energy of auroral electrons from measurements of the emission intensity of one of the bands of the 1NG system N_2^+, which is of undoubted interest for the development of methods of near real-time diagnostics of ionospheric plasma conditions during auroras.

1. EXPERIMENTAL DEPENDENCE OF $I_{630.0}/I_{427.8}$ on $I_{427.8}$

The proposed method for estimating the average energy of precipitating electrons relies on the experimental dependence of $\beta = I_{630.0}/I_{427.8}$ on λ427.8 nm. This dependence has been studied for many years, using ground-based [Christensen et al., 1987; Dashkevich et al., 2006] and aircraft [Eather, Mende, 1972; Gattinger, Vallance Jones, 1972] observations. Figure 1, *a* presents the results obtained in these works. We can see that β decreases progressively with increasing $I_{427.8}$. In this case, the absolute values of β obtained from aircraft measurements [Eather, Mende, 1972; Gattinger, Vallance Jones, 1972] exhibit a significant spread, whereas the emission intensity ratios measured during ground-based observations [Christensen et al., 1987; Dashkevich et al., 2006] agree well in absolute values. The reason for this agreement may be identical observation conditions [Christensen et al., 1987; Dashkevich et al., 2006]: experiments in the midnight sector of the auroral oval toward the magnetic zenith, identical recording equipment (scanning photometers), motionless radiation monitor, and, unlike [Eather, Mende, 1972; Gattinger, Vallance Jones, 1972], a large amount of experimental material. The results from the rocket experiment, described

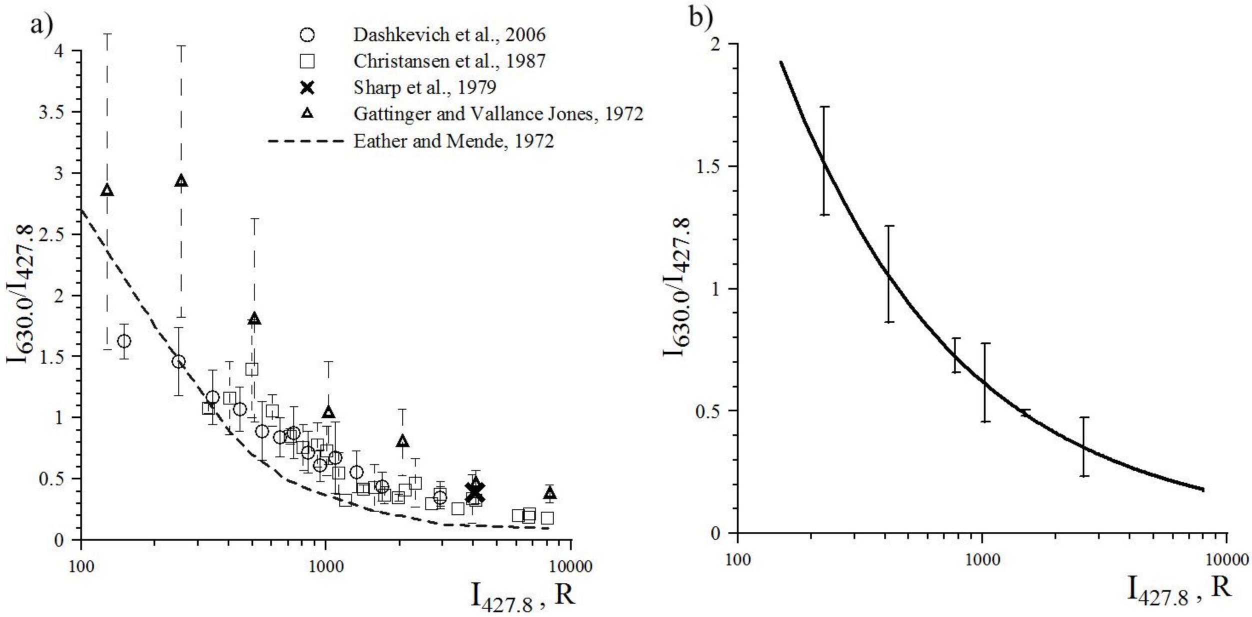

Figure 1. $\lambda I_{630.0}/I_{427.8}$ as function of $\lambda I_{427.8}$: *a* — experimental data; *b* — dependence averaged over data from ground experiments

in [Sharp et al., 1979], check well with those from ground-based observations. Figure 1, *b* plots β as function of $I_{427.8}$, averaged over experimental data from [Christensen et al., 1987; Dashkevich et al., 2006; Sharp et al., 1979].

The obtained dependence of β on $I_{427.8}$ is well approximated by the expression

$$\beta = 38.408 I_{427.8}^{-0.5959}, \qquad (1)$$

where $I_{427.8}$ is in R.

Expression (1) can be interpreted as a dependence reflecting the behavior of $I_{630.0}/I_{427.8}$ for typical auroras.

Given that $I_{630.0}/I_{427.8}$ weakly depends on the precipitating electron flux value, as shown in [Dashkevich, Ivanov, 2017], we can assume that an increase in $I_{427.8}$ for the typical aurora is generally determined by an increase in the average energy of auroral electrons. An increase in the average energy of the flux hardness causes auroral electrons to penetrate deeper into the ionosphere and hence $I_{427.8}$ to decrease due to the increasing role of the processes in deactivating the ^{1}D state of atomic oxygen.

2. INTENSITIES OF λ630.0 and λ427.8 nm EMISSIONS

The λ630.0 nm emission in auroras arises from the radiation transition $^1D \rightarrow {}^3P$ in the oxygen atom. When auroral electrons precipitate, the ^{1}D level of oxygen atom is excited in the following processes:

- direct collision of auroral electrons e* with oxygen atoms and molecules:

$$O + e^* \rightarrow O(^1D) + e^*,$$

$$O_2 + e^* \rightarrow O(^1D) + O + e^*;$$

- spontaneous radiation from the ^{1}S level of excited atomic oxygen:

$$O(^1S) \rightarrow O(^1D) + h\nu_{557.7};$$

- molecular oxygen ion deactivation (dissociative recombination) by thermal electrons e_{th}:

$$O_2^+ + e_{th} \rightarrow O(^1S) + O(^1D);$$

- collisional reactions with excited nitrogen atoms:

$$N(^2D) + O_2 \rightarrow NO + O(^3P, {}^1D),$$

$$N(^2D) + O \rightarrow N(^4S) + O(^3P, {}^1D),$$

$$N(^2P) + O_2 \rightarrow NO + O(^1S, {}^1D, {}^3P),$$

$$N^+ + O_2 \rightarrow NO^+ + O({}^1D, {}^1S).$$

The O(^{1}D) atom is metastable and lives for ~110 s; therefore, its deactivation occurs not only due to spontaneous transition to the ground level of atomic oxygen, but also as a result of collisional reactions with atmospheric gases and thermal electrons:

$$O(^1D) \rightarrow O(^3P) + h\nu,$$

$$O(^1D) + N_2 \rightarrow O + N_2,$$

$$O(^1D) + O_2 \rightarrow O + O_2,$$

$$O(^1D) + O \rightarrow O + O,$$

$$O(^1D) + e_{th} \rightarrow O + e_{th}.$$

The vertical profile of the 630.0 nm volume emission rate is determined as follows:

$$\eta_{630.0}(h)=A_{630.0}\left[\mathrm{O}\left({}^1\mathrm{D}\right),h\right],$$

where $\eta_{630.0}(h)$ is the 630.0 nm volume emission rate; $A_{630.0}$ is the corresponding Einstein coefficient; [O(^{1}D), h] is the atomic oxygen concentration in the ^{1}D state [cm^{-3}]; h is the height.

The concentration [O(^{1}D)] at h is found by solving the balance equation

$$\frac{d}{dt}\left[\mathrm{O}\left({}^1\mathrm{D}\right),h\right]=Q_{^1\mathrm{D}}(h)+A_{^1\mathrm{S}}\left[\mathrm{O}\left({}^1\mathrm{S}\right),h\right]+$$
$$+\sum_{i,j}k_{i,j}\left[N_i(h)\right]\left[N_j(h)\right]-A_{^1\mathrm{D}}\left[\mathrm{O}\left({}^1\mathrm{D}\right),h\right]-$$
$$-\sum_i k_i\left[\mathrm{O}\left({}^1\mathrm{D}\right),h\right]\left[N_i(h)\right],$$

where $Q_{^1\mathrm{D}}(h)$ is the rate of excitation of the ^{1}D level by direct impact; $k_{i,j}$ are reaction rate constants; $A_{^1\mathrm{D}}$ and $A_{^1\mathrm{S}}$ are Einstein coefficients for spontaneous transitions from the corresponding level; [$N_{i,j}$ (h)] are concentrations of i and j ionospheric components.

Vertical profiles of the rate of excitation of the ^{1}D state due to electron impact were calculated using the energy dissipation function and the energy costs, obtained by simulating electron transport in atmospheric gases [Ivanov, Kozelov, 2001] from the formulas

$$Q_{^1\mathrm{D}}(h)=P_\mathrm{O}(h)\frac{1}{\varepsilon_{^1\mathrm{D}}}\Phi\left(F(E),h\right),$$
$$\Phi\left(F(E),h\right)=\rho(h)\int_E\frac{E\cdot F(E)}{R(E)}\lambda\left(E,\frac{z(h)}{R(E)}\right)dE, \qquad (2)$$

where $\Phi(F(E), h)$ is the total energy dissipated at h; $P_\mathrm{O}(h)$ is the relative fraction of energy used to excite atomic oxygen at h; $\rho(h)$ is the neutral atmosphere density; $\varepsilon_{^1\mathrm{D}}$ is the energy cost of excitation of the ^{1}D state of oxygen atom; $z(h)$ is the mass traversed by an electron to a height h; $R(E)$ is the integral path length; $F(E)$ is the energy spectrum of precipitating electrons; $\lambda\left(E,\frac{z(h)}{R(E)}\right)$ is the dimensionless energy dissipation function [Sergienko, Ivanov, 1993].

The λ427.8 nm emission as the 1NG band of the system N_2^+ occurs due to the transition

$$\mathrm{N}_2^+\left(\mathrm{B}^2\Sigma_\mathrm{u}^+,v'=0\rightarrow \mathrm{X}^2\Sigma_\mathrm{g}^+,v''=1\right),$$

where v is the vibrational quantum number.

The 427.8 nm volume emission rate at h is defined as

$$\eta_{427.8}(h)=A_{01}\left[\mathrm{N}_2^+\left(\mathrm{B}^2\Sigma_\mathrm{u}^+\right),h\right],$$

where $\left[\mathrm{N}_2^+\left(\mathrm{B}^2\Sigma_\mathrm{u}^+\right),h\right]$ is the N_2^+ ion concentration in the state $\mathrm{B}^2\Sigma_\mathrm{u}^+, v'=0; A_{01}$ is the probability of radiative transition $\mathrm{B}^2\Sigma_\mathrm{u}^+, v'=0\rightarrow\mathrm{X}^2\Sigma_g^+, v''=1$.

The short lifetime of the term $\mathrm{B}^2\Sigma_\mathrm{u}^+$ (~10^{-7}s) makes it possible to neglect the collisional deactivation of this state. Assuming that this term is excited only by an electron impact and is deactivated due to radiation transitions to the term $\mathrm{X}^2\Sigma_\mathrm{g}^+$, the $\mathrm{N}_2^+\left(\mathrm{B}^2\Sigma_\mathrm{u}^+, v'=0\right)$ concentration under photochemical equilibrium conditions can be determined from the steady-state balance equation

$$0=Q_{\mathrm{B}^2}(h)-\sum_{v''}A_{0v''}\left[\mathrm{N}_2^+\left(\mathrm{B}^2\Sigma_\mathrm{u}^+\right),h\right],$$

where $Q_{\mathrm{B}^2}(h)$ is the rate of excitation of the N_2^+ ion state $\mathrm{B}^2\Sigma_\mathrm{u}^+, v'=0$ by an electron impact at h; $A_{0v''}$ is the probability of radiation transition $\mathrm{B}^2\Sigma_\mathrm{u}^+, v'=0\rightarrow\mathrm{X}^2\Sigma_\mathrm{g}^+, v''$.

Thus, the volume λ427.8 nm emission intensity at h

$$\eta_{427.8}(h)=\frac{A_{01}}{\sum_{v''}A_{0v''}}Q_{\mathrm{B}^2}(h).$$

Vertical profiles of the excitation rate $Q_{\mathrm{B}^2}(h)$ of the molecular nitrogen ion in state $\mathrm{B}^2\Sigma_\mathrm{u}^+, v'=0$ were also calculated using energy dissipation function (2) and energy costs:

$$Q_{\mathrm{B}^2}(h)=P_{\mathrm{N}_2}(h)\frac{q_{\mathrm{B}^2}}{\varepsilon_{\mathrm{B}^2}}\Phi\left(F(E),h\right),$$

where $P_{\mathrm{N}_2}(h)$ is the relative fraction of energy used to excite the nitrogen molecule at h; q_{B^2} is the Frank — Condon factor defining the relative population of the vibrational level $v'=0$ of the term $\mathrm{B}^2\Sigma_\mathrm{u}^+$; $\varepsilon_{\mathrm{B}^2}$ is the energy cost of excitation of the N_2^+ ion state $\mathrm{B}^2\Sigma_\mathrm{u}^+$; $\Phi(F(E), h)$ is the total energy dissipated at h; $F(E)$ is the energy spectrum of precipitating electrons.

The λ630.0 and 427.8 nm emission intensities in the aurora column are calculated from the formula

$$I_\lambda=\int_{h_2}^{h_1}\eta_\lambda(h)\,dh.$$

The emission intensities in electron auroras were numerically computed with the time-dependent model of the auroral ionosphere describing dissipative processes in ionospheric plasma initiated by precipitating auroral electron fluxes [Dashkevich et al., 2017]. MSIS-90 was utilized as the basic model of the neutral atmosphere. The pitch angle distribution of precipitating electrons was taken as isotropic in the lower hemisphere. The energy costs and parameters necessary for calculating excitation rates and dissipated energy from Formula (2) were borrowed from [Ivanov, Kozelov, 2001].

3. INFLUENCE OF THE SPECTRUM SHAPE AND THE ATMOSPHERE COMPOSITION ON E_{aver} ESTIMATION

The possibility of estimating auroral electron energy spectrum parameters from $I_{630.0}/I_{427.8}$ was first explored in [Rees, Luckey, 1974], where dependences of $I_{630.0}/I_{427.8}$ on $I_{427.8}$ were calculated for various characteristic energies of the Maxwellian distribution of precipitating electrons. Nonetheless, this work ignored the grade of influence of the electron spectrum shape and the neutral atmosphere composition on the calculated dependences. The absolute values of the emission intensity ratio β can depend on three main factors: the auroral electron energy spectrum shape, the neutral atmosphere model, and the efficiency of physical-chemical processes responsible for the population of the ^{1}D level of atomic oxygen. The grade of influence of these factors on the dependence of E_{aver} on β will be examined below.

The effect of the auroral electron energy spectrum shape on the β ratio has been studied for three types of distributions — Maxwellian, exponential, and monoenergetic respectively:

$$f(E)=\frac{F_E E}{2E_{\text{м}}^3}\exp\left(-\frac{E}{E_{\text{м}}}\right),$$

$$f(E)=\frac{F_E}{E_{\text{ср}}^2}\exp\left(-\frac{E}{E_{\text{ср}}}\right),$$

$$f(E)=\frac{F_E}{E}\delta(x-E),$$

where $E_m=E_{aver}/2$ is the characteristic energy.

Note that superposition of these distributions describes quite well the energy spectra of auroral electrons responsible for the generation of arcs, bands, and diffuse types of auroras. The average energy of precipitating electrons E_{aver} was analyzed in the range 0.5–15 keV, which is typical of auroral electrons that excite auroras [Vorobjev et al., 2013]. The nitric oxide concentration in the maximum of height profile $[NO]_{max}$ was assumed to be 10^8 cm^{-3}, which corresponds to average values in auroras [Dashkevich, Ivanov, 2019]. Figure 2, *a* presents the results of modeling of E_{aver} as function of $I_{630.0}/I_{427.8}$ for energy spectra of three types. E_{aver} is seen to change significantly with increasing β: then β increase from 0.1 to 10, the E_{aver} decreases from 14 to 0.5 keV. At the same time, the absolute values of E_{aver} do not show a strong change depending on the shape of the auroral electron energy spectrum. In Figure 2, *b* is the averaged β dependence of E_{aver}. Vertical lines are standard deviations, which in the β range from 0.1 to 10 vary from 3 to 20 %.

The neutral atmosphere model can influence the dependence of the average energy of precipitating electrons on the λ630.0 and λ427.8 nm emission intensity ratio by means of atomic oxygen. Atomic oxygen is an immediate source of the λ630.0 nm emission, and variations in the atomic oxygen concentration can be expected to cause significant changes in estimates of E_{aver} from β. In [Shepherd and Gerdjikova, 1988; Gattinger et al., 1996], the effect of the atomic oxygen concentration on the λ557.7 and λ427.8 nm emission intensity ratio was examined. The authors concluded that the $I_{557.7}/I_{427.8}$ variability observed in experiments can be explained by variations in the atomic oxygen concentration in the range 0.5–2$[O]_{MSIS}$. Note that this range of atomic oxygen concentrations fits the neutral atmosphere model MSIS-90 for various solar and geomagnetic activity levels.

The simulated dependences of the average energy of auroral electrons with Maxwellian energy distribution on the λ630.0 and λ427.8 nm emission intensity ratio for different atomic oxygen concentrations [O] belonging to the range 0.5–2 $[O]_{MSIS}$ are shown in Figure 3, *a*. The divergences between E_{aver} values corresponding to different [O] concentrations are seen to be small. In Figure 3, *b* is the averaged dependence E_{aver} on β. Vertical lines denote standard deviations that do not exceed 12 % at β=0.1÷2 and 20 % at β=2÷10.

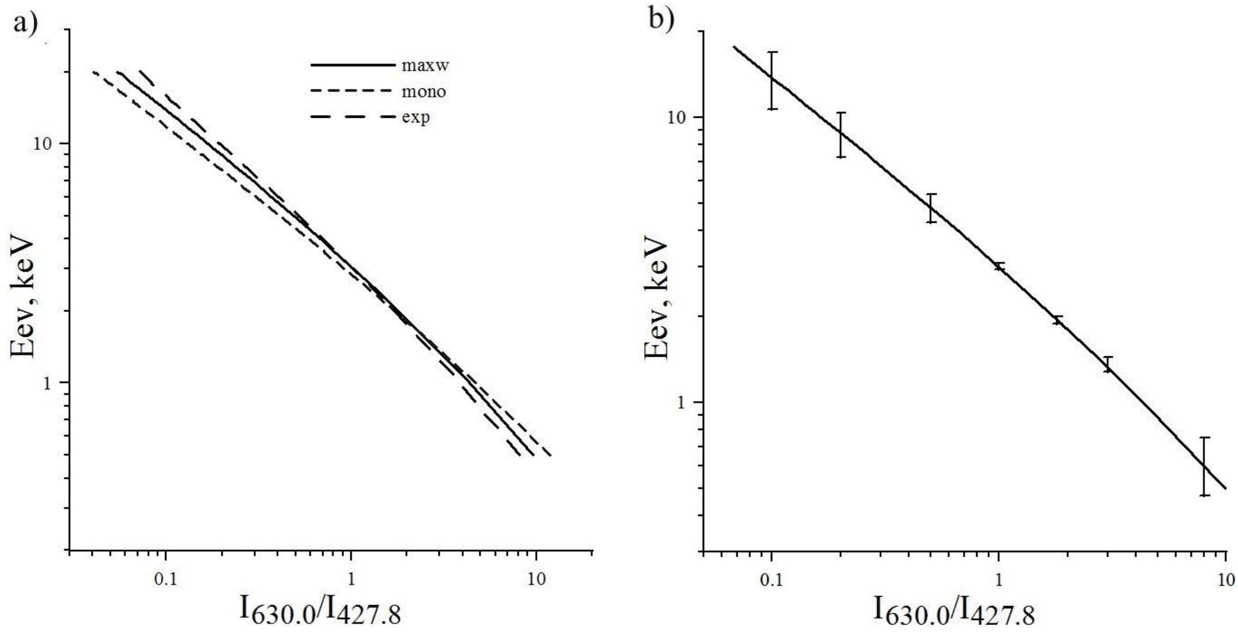

Figure 2. Average energy E_{aver} as function of $I_{630.0}/I_{427.8}$: *a* — for energy spectrum of different type; *b* — averaged dependence

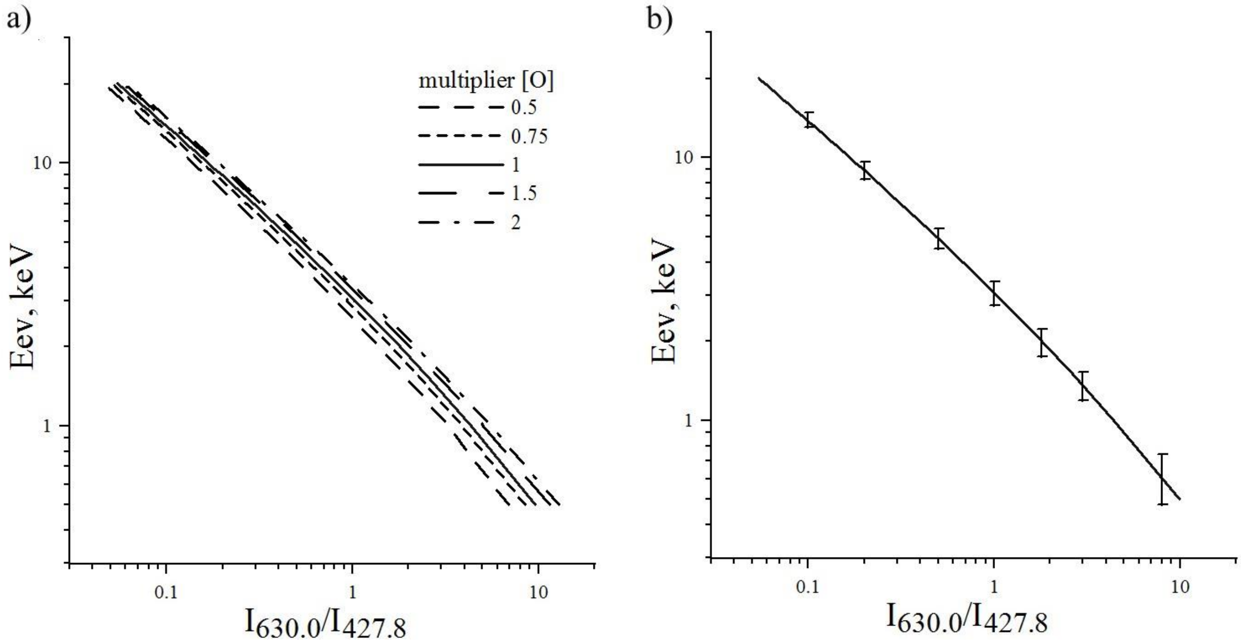

Figure 3. Average energy E_{aver} as function of $I_{630.0}/I_{427.8}$: *a* — for different atomic oxygen concentrations; *b* — averaged dependence

The insignificant effect of the atomic oxygen [O] concentration on the β dependence of E_{aver} can be explained by the fact that atomic oxygen is not only a source of the λ630.0 nm emission due to direct electron impact, but also the main deactivator of the $O(^1D)$ state in $O(^1D)+O$. Figure 4, *a*, *b* plots the λ630.0 nm emission intensity as function of the average energy of precipitating electrons with and without regard to the deactivation reaction of the ^1D state of atomic oxygen. Considering the deactivation of the ^1D state in $O(^1D)+O$ is seen to cause a decrease in the grad of influence of the [O] concentration on the 630.0 nm emission intensity and hence, as could be expected, a less significant effect of the atomic oxygen concentration variations on the dependence of the average energy of precipitating electrons on $I_{630.0}/I_{427.8}$.

Physical-chemical processes, which determine population of the ^1D level of atomic oxygen, exert some effect on the form of the β dependence of E_{aver} by means of nitric oxide NO. Nitric oxide is a strong deactivator of the molecular oxygen ion O_2^+, which leads to a decrease in the contribution of the dissociative recombination reaction $O_2^+ + e_{th} \rightarrow O(^1D) + O(^1S)$ to the excitation of the ^1D state of atomic oxygen, as well as to a decrease in the contribution to the excitation of the ^1D state due to the radiation transition $O(^1S) \rightarrow O(^1D) + h\nu$. Figure 5, *a* plots the average energy of precipitating electrons with Maxwellian

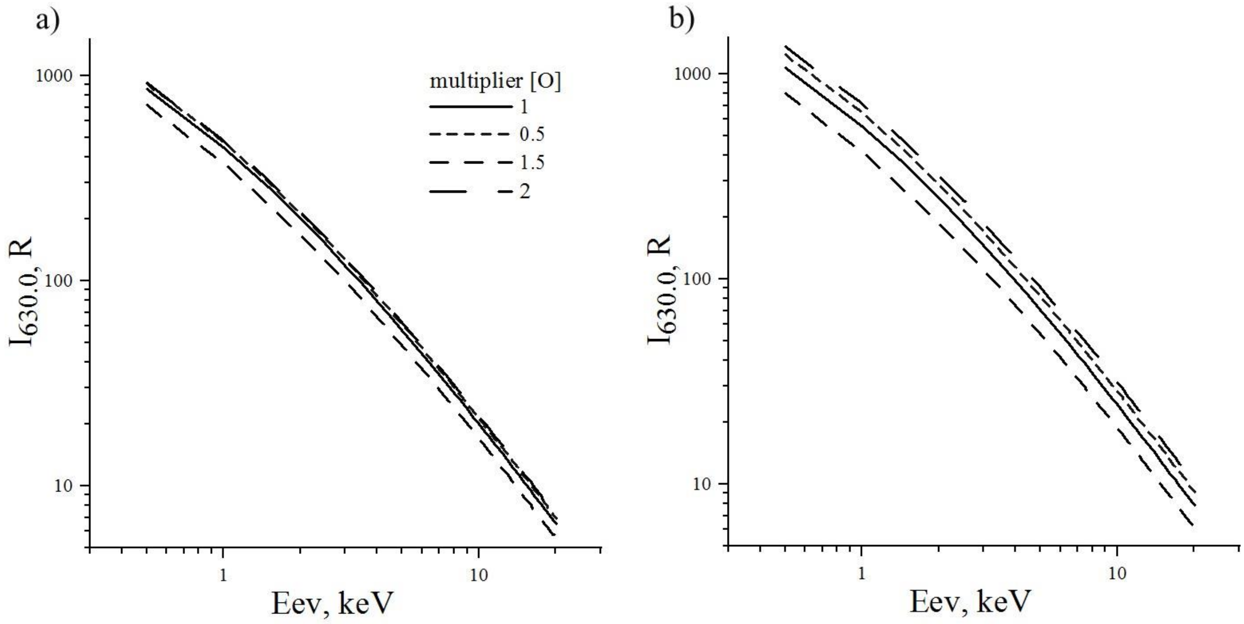

Figure 4. Dependence of the λ630.0 nm emission intensity on the average energy of precipitating electrons with (*a*) and without (*b*) regard to deactivation of the ^1D state of atomic oxygen

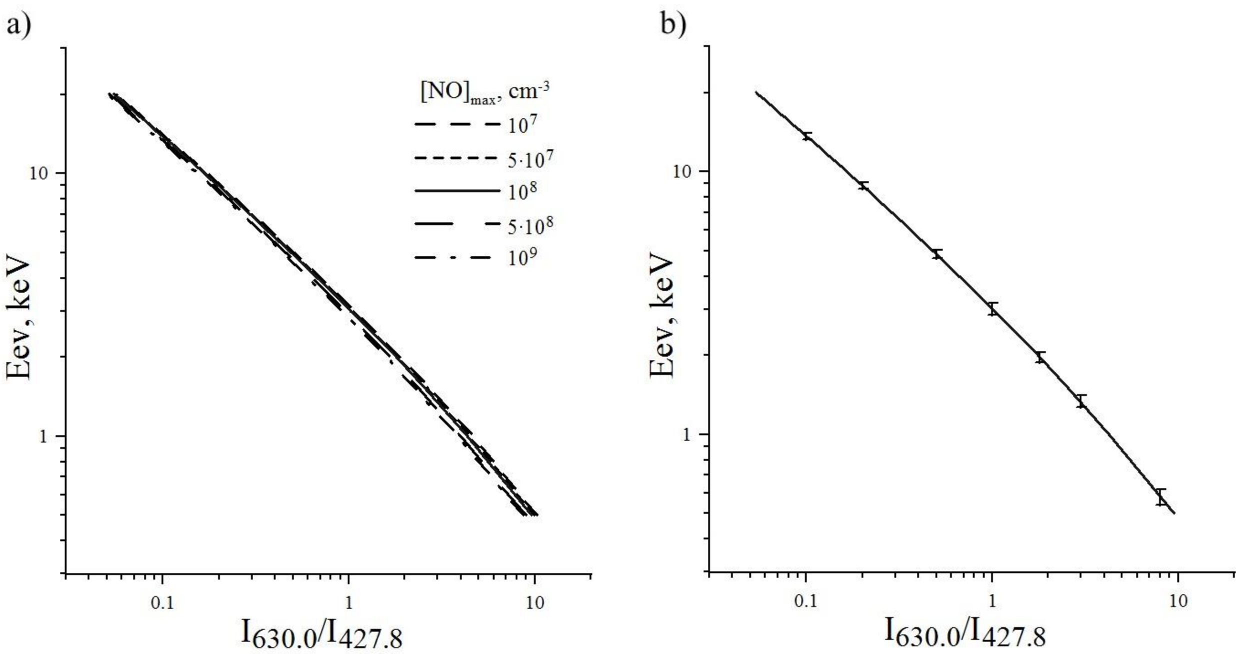

Figure 5. Average energy E_{aver} as function of $I_{630.0}/I_{427.8}$: *a* — for different nitric oxide concentrations; *b* — averaged dependence

energy distribution as function of $I_{630.0}/I_{427.8}$. The calculations have been carried out in the neutral atmosphere model MSIS-90 for nitric oxide concentrations at the height profile maximum $[NO]_{max}$ are in the range $10^{7} \div 10^9$ cm^{-3}, which corresponds to $[NO]_{max}$ observed in experiments [Swider, Narcisi, 1977; Dashkevich, Ivanov, 2019]. The changes in the β dependence of E_{aver} are seen to be insignificant. In Figure 5, *b* is the averaged β dependence of E_{aver}. Vertical lines indicate the standard deviations that at η=0.1÷10 do not exceed 7 %.

Thus, the energy spectrum shape, the neutral atmosphere model, and the nitric oxide concentration have a slight effect on the dependence of E_{aver} on $I_{630.0}/I_{427.8}$. Deviations from E_{aver} do not exceed 20 %.

4. RELATIONSHIP BETWEEN THE AVERAGE ENERGY OF PRECIPITATING ELECTRONS AND λ427.8 nm EMISSION INTENSITY

Taking into account the experimental dependence of the λ630.0 and λ427.8 nm emission intensity ratio on the λ427.8 nm emission intensity and the modeled dependences of E_{aver} on $I_{630.0}/I_{427.8}$, we can identify a relationship between E_{aver} and $I_{427.8}$. This dependence, averaged with respect to the above-described effects of the auroral electron energy spectrum shape, atomic oxygen and nitric oxide concentrations, is illustrated in Figure 6.

The resulting dependence is well approximated by the expression

$$E_{cp} = 0.251\left(I_{427.8}\right)^{0.405}, \quad (3)$$

where E_{aver} is in keV; $I_{427.8}$, in R.

Vallance Jones et al. [1987] present the results of optical observations of the λ427.8 nm emission intensity and estimates of the average energy of auroral electrons from incoherent scatter radar data obtained from simul-

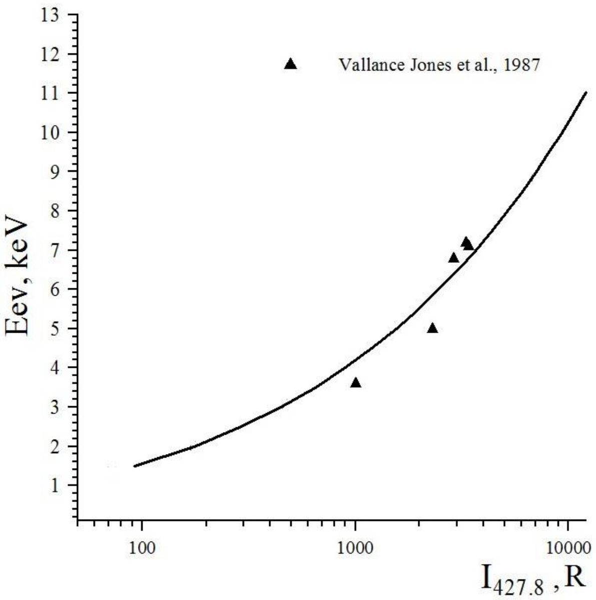

Figure 6. Average energy of precipitating electrons as function of the λ427.8 nm emission intensity

taneous measurements. Figure 6 shows a satisfactory agreement between evaluation curve (3) for E_{aver} and experimental data [Vallance Jones et al., 1987], indicated by triangles.

CONCLUSION

The paper has explored the possibility of estimating the average energy of precipitating electrons E_{aver} by measuring the λ427.8 nm emission intensity $I_{427.8}$. The method is based on the experimental dependence of the λ630.0 and λ427.8 nm emission intensity ratio on the λ427.8 nm emission intensity. We have numerically analyzed the effects of three factors on the dependence of E_{aver} on $I_{630.0}/I_{427.8}$: the auroral electron energy spectrum shape, the neutral atmosphere model, and the nitric oxide NO concentration. We have shown that the influence of the energy spectrum shape, the neutral atmosphere model, and the NO concentration on the $I_{630.0}/I_{427.8}$ dependence of E_{aver} does not exceed 20 %. We have calculated the dependence of the average energy of auroral electrons on the λ427.8 nm emission intensity in auroras. The analytical approximation of the obtained dependence is presented. The approximation can be used for developing methods of real-time diagnostics and prediction of ionospheric plasma conditions during auroras.

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