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DIAGNOSTICS OF EMISSION INTENSITIES AND ELECTRON DENSITY IN AURORAS BASED ON EMPIRICAL PRECIPITATION MODELS

Zh.V. Dashkevich
Polar Geophysical Institute,
Apatity, Russia, zhanna@pgia.ru

V.E. Ivanov
Polar Geophysical Institute,
Apatity, Russia, ivanov@pgia.ru

Abstract. We have studied the influence of the precipitating electron spectrum shape on the integral intensity of emissions λ391.4 nm 1NG N_2^+, λ670.4 mn 1PG N_2, λ337.1 nm 2PG N_2, λ320.0 nm VK N_2, λ127.3 nm LBH N_2, atomic oxygen emissions λ557.7 and λ630.0 nm, total electron content in the vertical column of aurora. The integral characteristics of the emission intensity and the total electron content are shown to depend weakly on the energy spectrum shape and to be determined mainly by average energy values E_{ev} and energy flux value F_E of precipitating electrons. An algorithm is proposed for diagnosing the planetary distribution of emission intensities and electron density in auroras based on data from empirical electron precipitation models, without making a priori assumptions about the shape of the energy spectrum of precipitating electrons

Keywords: auroras, electron precipitation, excitation efficiency, auroral emissions, electron density, planetary distribution.

INTRODUCTION

One of the key issues in diagnostics and prediction of conditions of the disturbed polar ionosphere is forecasting of the planetary distribution of the auroral intensity in different spectral ranges and the electron density during magnetospheric disturbances. Attempts to create global models of auroral glow have been made in [Ivanov et al., 1993; Vorobjov et al., 2013]. The experimental basis for these studies was empirical precipitation models representing the spatial distribution of average energies and precipitating electron fluxes for different levels of magnetic activity. Ivanov et al. [1993] used an empirical model of the planetary distribution of electron precipitation, proposed in [Spiro et.al, 1982], to calculate integral intensities of auroral emissions. The auroral intensities were calculated under the assumption that the energy spectrum of the precipitating electron flux is exponential. Vorobjov et al. [2013] exploited the auroral precipitation model presented in [Vorobyov, Yagodkina, 2005, 2007] to calculate integral glow intensities. The glow intensities were calculated under the assumption that the energy spectrum of the precipitating electron flux has Maxwellian distribution. In both works, the authors made an a priori assumption about the shape of the energy spectrum of the precipitating electron flux for the calculations.

This paper describes and justifies a technique capable of working out effective algorithms for calculating the planetary distribution of auroral intensities and the electron density, without making assumptions about the shape of the energy spectrum of the precipitating electron flux, but using only average energies and energy fluxes of precipitating electrons presented in empirical auroral precipitation models [Spiro et al., 1982; Hardy et al., 1985; Vorobjev et al., 2013].

CALCULATION METHOD

Let us analyze the influence of precipitating electron flux parameters on the integral emission intensity and the electron density in the vertical column of auroras. By the flux parameters is meant the shape of the energy spectrum, the energy flux, and the average energy of precipitating electrons. Let us introduce a concept of emission excitation efficiency defined as the ratio of the integral intensity of emission with a wavelength λ to the total precipitating electron energy flux $\Phi_\lambda = I_\lambda / F_E$, where I_λ is the integral emission intensity measured in Rayleigh; F_E is the energy flux of precipitating electrons (erg·cm^{-2}s^{-1}).

Thus, the emission excitation efficiency is equal to the integral emission intensity conditioned by precipitation of electrons with an energy flux equal to 1 erg·cm^{-2}s^{-1}.

The column intensity is the total intensity in the vertical column of aurora and can be calculated from the vertical profile of the volume emission intensity $I_\lambda = \int_h Q_\lambda(h)dh$, where $Q_\lambda(h)$ is the volume emission intensity with a wavelength λ at a height h (cm^{-3}s^{-1}).

Similarly, we assess the efficiency of formation of the total electron content in the aurora column $\Phi_e = N_e / F_E$, $N_e = \int_h n_e(h)dh$, where N_e is the total electron content in the aurora column in cm^{-2}; $n_e(h)$ is the electron density at a height h (cm^{-3}).

Thus, the efficiency of formation of the total electron content is equal to the total electron content in the aurora column, conditioned by precipitation of electrons with an energy flux of 1 erg·cm^{-2}s^{-1}.

The emission intensities and the electron density were calculated using a physicochemical model of excited polar ionosphere. The model presented in

[Dashkevich et al., 2017] allows us to calculate the vertical concentration profiles of 17 main excited and ionized atmospheric gas components and the electron density during auroral precipitation. Input parameters of this model are the energy spectrum of precipitating electrons at the upper boundary of the ionosphere and the neutral atmosphere model. 56 physicochemical reactions describe the redistribution of energy released due to electron precipitation. In addition, the model correctly considers the electron-vibrational kinetics in the processes of excitation of triplet states N_2. The vertical profiles of formation rates of excited atmospheric gas components were calculated using the energy dissipation function and «energy prices» obtained by simulating the electron transport in atmospheric gases [Ivanov, Kozelov, 2001; Sergienko, Ivanov, 1993].

To simulate the emission intensities, we have selected the most characteristic and intense bands observed in auroras, namely, the λ391.4 nm emission of the first negative system 1NG N_2^+, the λ670.4 nm emission of the first positive system 1PG N_2, the 337.1 nm emission λ of the second positive system 2PG N_2, the λ 320.0 nm emission of the Vegard—Kaplan system VK N_2, the λ127.3 nm emission of the Lyman-Birge-Hopfield system LBH N_2, λ 557.7 and λ 630.0 nm atomic oxygen emissions. The optical transitions corresponding to the selected emissions are shown in Table.

Optical transitions of auroral emissions

Transitions O			λ, nm
$^1S \rightarrow {}^1D$			557.7
$^1D \rightarrow {}^3P$			630.0
Transitions N_2	v′	v″	λ, nm
1PG $B^3\Pi_g \rightarrow A^3\Sigma_u^+$	5	2	670.4
2PG $C^3\Pi_u \rightarrow B^3\Pi_g$	0	0	337.1
VK $A^3\Sigma_g^+ \rightarrow X^1\Sigma_g^+$	1	9	320.0
LBH $a^1\Pi_g \rightarrow X^1\Sigma_g^+$	6	0	127.3
Transitions N_2^+			
1NG $B^2\Sigma_u^+ \rightarrow X^2\Sigma_g^+$	0	0	391.4

v′, v″ are the vibrational quantum numbers of the upper and lower terms respectively.

The electron density was calculated under the condition of thermodynamic equilibrium as the sum of the ion concentration at a height *h*:

$$n_e = \left[N_2^+\right] + \left[O_2^+\right] + \left[O^+\left({}^4S\right)\right] + \left[O^+\left({}^4D\right)\right] + \\ + \left[O^+\left({}^4P\right)\right] + \left[NO^+\right] + \left[N^+\right].$$

The calculations were made in the neutral atmosphere model MSIS-E-90 [Hedin, 1991]; the data is taken from the website [https://ccmc.gsfc.nasa.gov/modelweb/models/msis_vitmo.php; https://ccmc.gsfc.nasa.gov/modelweb/models/msis_vitmo.php]. The electron source was placed at a height of 700 km.

To study the effect of the spectrum shape on the efficiency of emission excitation and the electron density formation, as input parameters we have chosen precipitating electron flux energy spectra of three types: monoenergetic, with exponential energy distribution, and with Maxwellian energy distribution:

$$f(E) = F_E \delta(x - E),$$
$$f(E) = \frac{F_E}{E_0^2} \exp\left(-\frac{E}{E_0}\right), \qquad (1)$$
$$f(E) = \frac{F_E}{2E_0^3} E \exp\left(-\frac{E}{E_0}\right).$$

Distributions of these three types and their combinations describe the spectra of precipitating electrons observed in auroras.

Figure 1 shows spectra with Maxwellian and exponential energy distributions for different average energies of precipitating electrons, F_E=1 erg $\cdot cm^{-2}s^{-1}$.

The pitch angle distribution was taken as isotropic in the lower hemisphere. The calculations are made for average energies in the range 0.1–20 keV, which is typical for auroral electrons exciting auroras [Spiro et al., 1982; Hardy et al., 1985, 1987; Vorobjev et al., 2013].

RESULTS

Empirical models of auroral precipitation include the planetary distribution of energy fluxes and average energies of precipitating electrons. Let us examine the dependences of emission excitation efficiencies Φ_λ and the efficiency of formation of the total electron content Φ_e on the average energy of the precipitating electron flux E_{av}.

Emissions of the first negative system of molecular nitrogen occur only due to direct excitation by electron impact, hence they can serve as an effective tool for estimating the energy exchange between the magnetosphere and the ionosphere. Figure 2 presents the estimated dependences of the efficiency of 1NG N_2^+ λ 391.4 nm emission excitation on the average energy of precipitating electrons E_{av} for energy spectra of auroral electrons of three types (1). We can see that the ratio of the column intensity of the λ391.4 nm emission to the energy

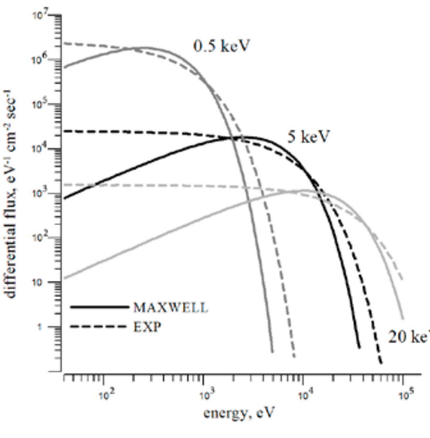

Figure 1. Energy spectra with Maxwellian and exponential energy distributions (1) for different average energies of precipitating electrons

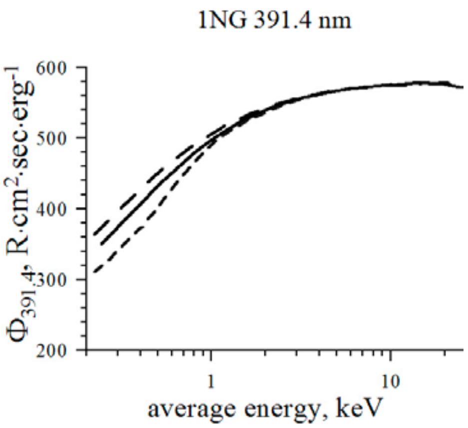

Figure 2. Efficiency of the λ 391.1 nm emission excitation calculated for the spectrum of precipitating electrons of three types: long dashes indicate a flux with exponential distribution; short dashes, monoenergetic flux; solid line, a flux with Maxwellian distribution (1)

introduced into the ionosphere by auroral electrons depends weakly on initial differential particle flux type (1). A maximum deviation $\Phi_{391.4}$ from the mean value in the average electron energy range considered does not exceed 8 %.

Figure 3 depicts dependences of the efficiencies on the average energy of precipitating electrons $\Phi_\lambda(E_{av})$ calculated for emissions λ 670.4 nm 1PG N_2, λ 337.1 nm 2PG N_2, λ 320.0 nm VK N_2, and λ 127.3 nm LBH N_2. In contrast to the λ 391.4 nm emission, along with the direct impact, the processes of energy redistribution due to chemical reactions contribute to the excitation of the above emissions [Dashkevich et al., 2017]. It is obvious that for these emissions $\Phi_\lambda(E_{av})$ also weakly depends on the shape of the energy spectrum of the precipitating electron flux. Maximum deviations are observed only for the λ 320.0 nm VK N_2 emission whose excitation depends strongly on the physicochemical processes of energy transport. The maximum deviation of $\Phi_{320.0}$ from the mean value does not exceed 12 %.

Figure 4 shows the dependencies $\Phi_\lambda(E_{av})$ for the λ 557.7 and λ 630.0 nm excited atomic oxygen emissions whose excitation is also significantly contributed by energy redistribution as a result of chemical reactions occurring in the atmosphere due to electron precipitation [Dashkevich, Ivanov, 2018]. The excitation efficiencies of these atomic oxygen emissions $\Phi_{557.7}$ and $\Phi_{630.0}$ are seen to depend weakly on the shape of the energy spectrum of the precipitating electron flux as well; the maximum deviation from the mean value is no more than 10 %.

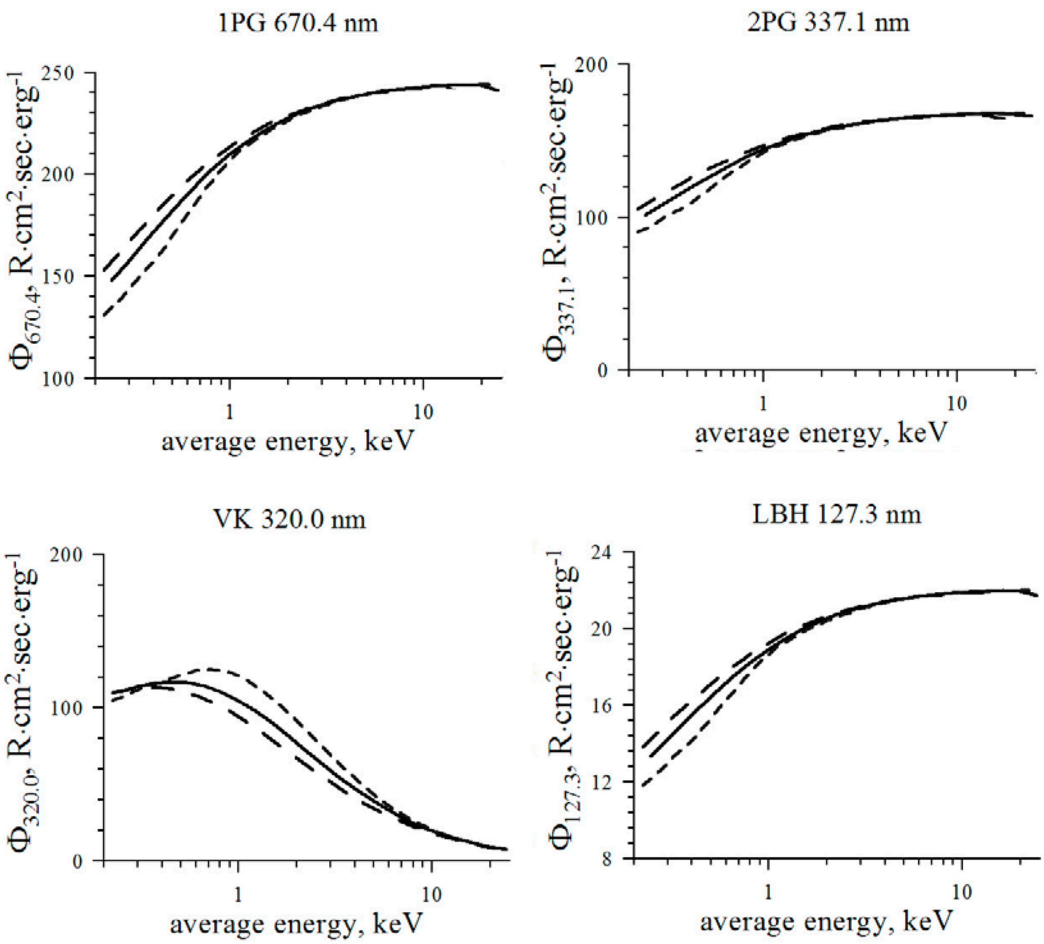

Figure 3. Excitation efficiencies of molecular nitrogen emissions calculated for the precipitating electron spectrum of three types: long dashes mark an exponential distribution; short dashes, a monoenergetic flux; solid line, Maxwellian distribution (1)

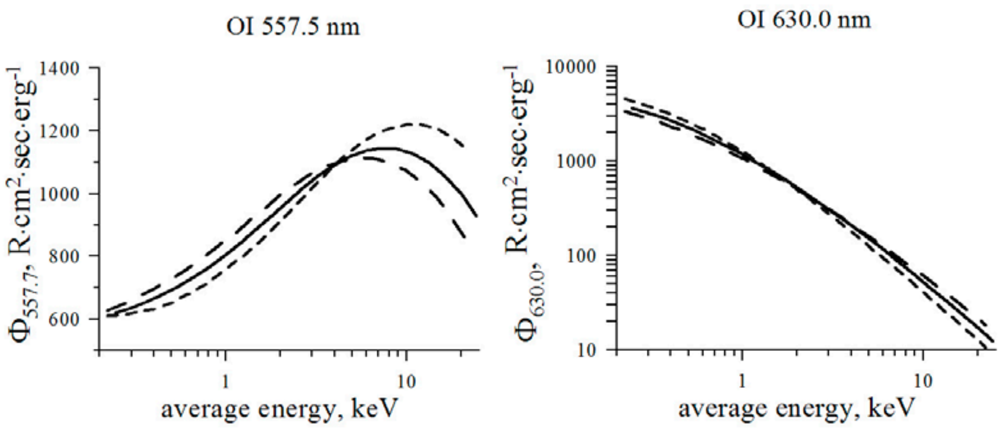

Figure 4. The same for excited atomic oxygen emissions

The weak dependence of $\Phi_\lambda(E_{av})$ on the shape of the energy spectrum of the precipitating electron flux allows us, in algorithms capable of forecasting the planetary distribution of emission intensity in auroras with the aid of empirical auroral precipitation models, to use the functional connection

$$I_\lambda = F_E \Phi_\lambda \left(E_{av}\right), \quad (2)$$

where I_λ is the column intensity of emission with a wavelength of λ; F_E and E_{av} are the energy flux and the average electron energy represented in empirical auroral precipitation models. The value of $\Phi_\lambda(E_{av})$ is defined as the averaged value of corresponding curves in Figures 1–3.

In addition to forecasting the planetary distribution of emission intensities in the optical range, of considerable interest is forecasting of the total electron content. Figure 5 shows the dependence of the efficiency of the electron density formation $\Phi_e(E_{av})$ on the average energy of precipitating electrons, calculated for energy spectrum of precipitating electron flux (1) of three types. It can be seen that the maximum deviations Φ_e from the mean value do not exceed 5 % in the range of average precipitating electron energies 0.1–20 keV considered. We can therefore use a functional connection similar to (2) to calculate the planetary distribution of the electron density in the aurora column, $N_e = F_E \Phi_e \left(E_{av}\right)$,

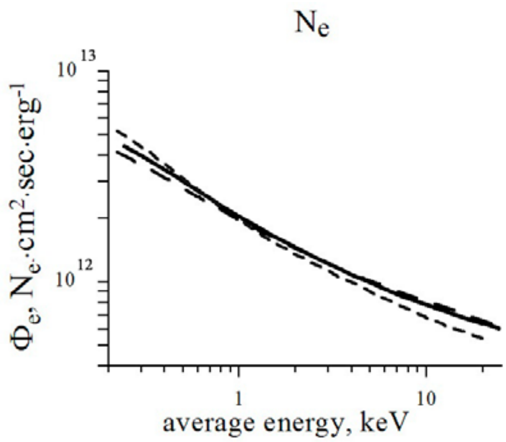

Figure 5. Efficiency of the total electron content formation in the aurora column, calculated for the precipitating electron spectrum of three types: long dashes mark exponential distribution; short dashes, a monoenergetic flux; solid line, Maxwellian distribution (1)

where N_e is the total electron content in the vertical aurora column; F_E and E_{av} are the energy flux and the average electron energy.

Figure 6 exemplifies the planetary distribution of the λ 391.4 and λ 557.7 nm emission intensities and the electron density in the aurora column, calculated using the proposed technique and data from the empirical auroral electron precipitation model [Vorobjev et al., 2013] for moderate auroral activity AL= –300, Dst = –5.

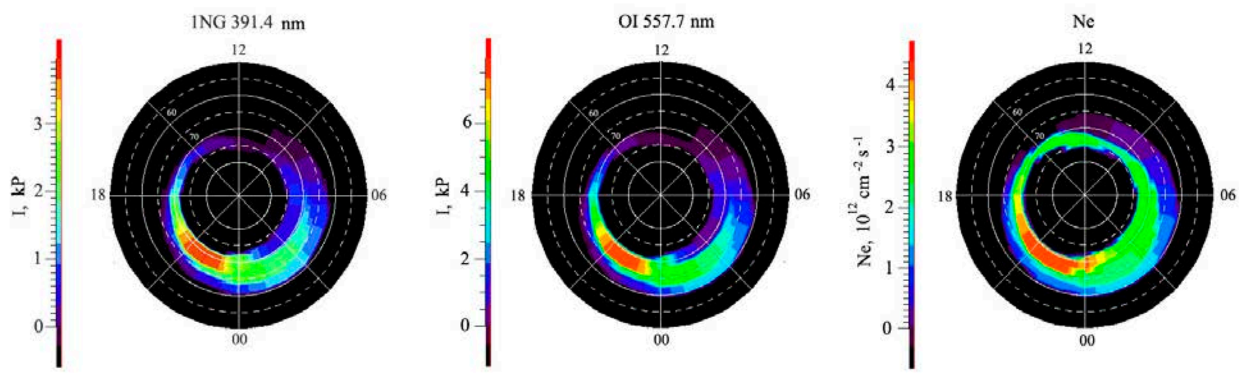

Figure 6. Planetary distributions of the λ 391.4 and λ 557.7 nm emission intensities and the electron density in the aurora column (AL= –300, Dst= –5)

CONCLUSION

We have formulated the concept of the emission excitation efficiency Φ_λ, which is defined as the ratio of the column intensity of emission with a wavelength λ to the total precipitating electron energy flux, and by analogy, of the efficiency of formation of the total electron content in the aurora column Φ_e. We have studied the influence of the precipitating electron flux parameters, namely the spectrum shape and the average energy, on the excitation efficiency of λ 391.4 nm emissions of the first negative system N_2^+, λ 670.4 nm of the first positive system N_2, λ 337.1 nm of the second positive system N_2, λ 320.0 nm of the Vegard—Kaplan system N_2, λ 127.3 nm emission of the Lyman—Burge—Hopfield system N_2, the λ557.7 and λ 630.0 nm atomic oxygen emissions, as well as on the efficiency of formation of the total electron content in the vertical aurora column. Φ_λ and Φ_e were calculated for the energy spectrum of auroral electrons of three types: monoenergetic, exponential, and with Maxwellian distribution. The average electron energy varied from 0.1 to 20 keV, which is typical of auroral precipitation. The efficiencies of Φ_λ and Φ_e are shown to depend weakly on the shape of the energy spectrum and be determined mainly by average energies E_{av} of the precipitating electron flux. The estimated dependencies of Φ_λ and Φ_e on the average energies allow us to develop effective algorithms for calculating the planetary distribution of aurora intensities and the total electron content in auroras with the aid of empirical electron precipitation models, without making a priori assumptions about the shape of the energy spectrum of the precipitating electron flux.

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