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DEPENDENCES OF AURORAL 5577 Å AND 6300 Å EMISSION RATES ON THERMOSPHERIC DENSITY VARIATIONS

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Abstract: The emission rates of auroral 5577 Å and 6300 Å atomic oxygen lines and the energy deposition rates are calculated to investigate the dependences of these rates on the condition of the neutral atmosphere. The atmospheric model used is the MSIS-86 empirical model developed by A. E. HEDIN (J. Geophys. Res., **92**, 4649, 1987), and the method of calculation is the two stream approach applied to the electron transport equation by K. STAMNES (J. Geophys. Res., **86**, 2405, 1981). The altitude profiles of N_2, O_2 and O which are main species in the thermosphere vary with the magnetic activity level represented by the *Ap* index. Corresponding to these variations, auroral 5577 and 6300 Å emission rates are found to change by a factor of 2–3, particularly when low energy electrons precipitate into the atmosphere, while the variations in the energy deposition rate are found to be small.

1. Introduction

Accurate estimations of the rates of optical emissions and energy depositions produced by precipitating particles are significantly important for understanding auroral physical processes. The penetration of primary auroral electrons into the atmosphere has been discussed theoretically by a number of workers. The first widely used model was developed by REES (1963), and subsequently by WALT *et al.* (1969), BERGER *et al.* (1970), BANKS *et al.* (1974), and STAMNES (1981). In association with the progress in the theoretical work, comparisons between observed and calculated auroral emission rates were made using simultaneous observations of precipitating particles and auroral emissions (*e.g.*, REES *et al.*, 1977; SHARP and TORR, 1979; GERDJIKOVA and SHEPHERD, 1987; SOLOMON *et al.*, 1988). The calculated auroral emission rates are affected by various factors, such as (1) the method of calculation used, (2) the values of cross sections for electron impact with the neutral atmospheres and coefficients of chemical reactions, and (3) the model of the neutral atmosphere.

In the present paper we calculate the emission rates of auroral OI 5577-Å and OI 6300-Å lines and the energy deposition rates using the MSIS-86 atmosphere model developed by HEDIN (1987) to investigate the dependences of these rates on the condition of the neutral atmosphere.

2. Model Calculation

The method of the calculation used in the present paper is a two stream approach

to the electron transport equation, which is one of the most prevailing methods for the study of the transport and thermalization of auroral electrons in the atmosphere (BANKS *et al.*, 1974; SOLOMON *et al.*, 1988). Detailed description of this method is given by STAMNES (1981). In the case of the electron transport and energy degradation problem, this method assumes 'two stream' electron fluxes; *i.e.*, electron fluxes have an isotropic pitch angle distribution in both of the upward and downward hemispheres. The total elastic cross sections for electron impact on N_2, O_2 and O used in our calculation are the same with those adopted by STAMNES and REES (1983). The inelastic cross sections, which are identical with those used by GREEN and STOLARSKI (1972) and BANKS *et al.* (1974) except for the excitation cross sections of $O(^1S)$ and $N_2(B^3\pi_g)$, are modified by the energy degradation routine of SWARTZ (1985) to conserve both the input and output total energies. The value obtained from the recent laboratory measurements by SHYN *et al.* (1986) is used for the excitation process of $O(^1S)$. For the excitation of $N_2(B^3\pi_g)$, the value obtained from the laboratory measurement of SHEMANSKY and BROADFOOT (1971b) is used based on the results of the airborne auroral observation of REES *et al.* (1976).

The atmospheric model adopted in our study is the MSIS-86 model (HEDIN, 1987). The first MSIS model was developed in 1977, and it was revised in 1983 (HEDIN *et al.*, 1977a, b; HEDIN, 1983). The MSIS-86 model is the third version. This emprical model is the most up-to-date atmospheric model which is constructed using the mass spectrometer data from seven satellites and numerous rocket measurements as well as the data from five ground-based incoherent scatter radar stations.

In this model calculation the atmosphere above Syowa Station is assumed by selecting four parameters as follows: geographic location, 69.00°S, 39.58°E (Syowa Station), the day of year, 172 (winter solstice), $F_{10.7}$ solar flux, 150.0×10^{-22} W/m²Hz which corresponds to the normal solar activity level, and 0000 UT which is nearly equal to magnetic midnight at Syowa Station. On the other hand, an *Ap* index is chosen as *Ap*=4, 10, 20, 30, ···, until 100 to see the dependences of thermospheric density variations on magnetic activity. The *Ap* index is the diurnal average of three-hour *Ap* indices which are the transformation of *Kp* to a linear scale. The quiet, moderate and disturbed periods of magnetic activity roughly correspond to the *Ap* index ranges of 1–15, 15–30, and 30∼, respectively.

In the present paper we assume that the neutral atmosphere comprises three main species (N_2, O_2, O). Figure 1 shows the dependences of the height profiles of these three species on the *Ap* index. It is noted that the densities of N_2 and O_2 are independent of magnetic activity below the altitude of 130 km, while the densities increase above this altitude as the *Ap* index increases. On the other hand, the density of O below the altitude of 320 km is found to decrease by about a factor of 1.5 as the *Ap* index increases.

Using this atmospheric model, we calculated the height profiles of auroral 5577 and 6300 Å emission rates in a steady state reaction scheme. Table 1 shows the types of chemical reactions, their rate coefficients, branching ratios and transition probabilities employed. The auroral green line at 5577 Å is emitted by the 2^1S–2^1D transition of OI. The mechanisms responsible for the production and loss of auroral $O(^1S)$, however, have not been established. The historical reviews on the studies of the green line

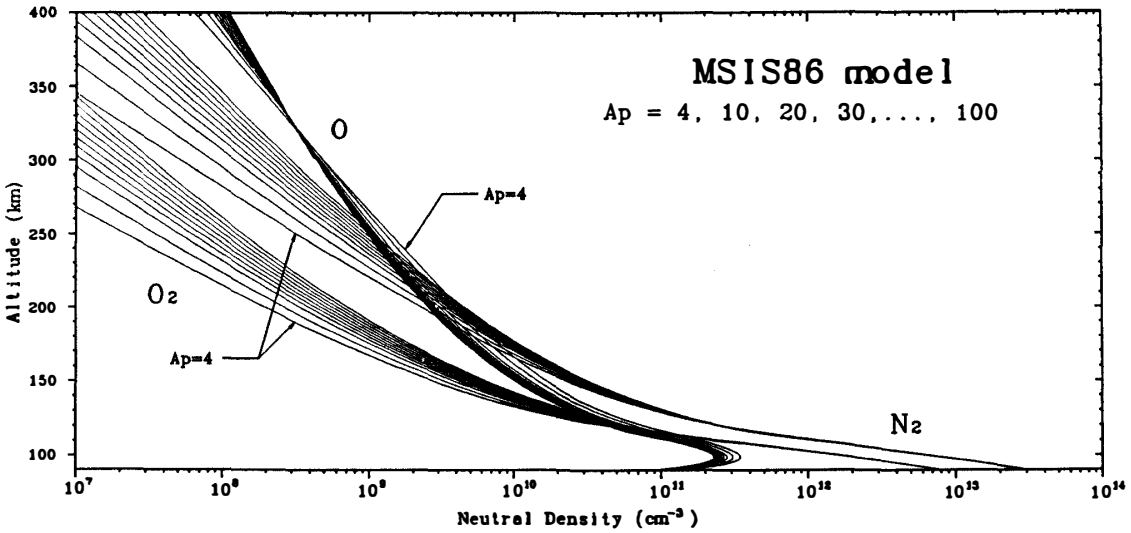

Fig. 1. Variations of the density profiles of N_2, O_2 and O for different Ap indices calculated using the atmospheric model MSIS-86 given by HEDIN *(1987). The fixed parameters used are given in the text. The density profiles are calculated for the Ap indices of 4, 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100.*

Table 1. Chemical reaction coefficients used in the calculation of 5577- and 6300-Å emissions.

Reaction	Coefficient	Reference
$N_2+e^*\rightarrow N_2(B^3\pi_g)+e^*$	$v''=0$–12	SHEMANSKY and BROADFOOT (1971b)
$N_2+e^*\rightarrow N_2(A^3\Sigma c^+)+e^*$	$v''=0$–13	GREEN and STOLARSKI (1972), CARTWRIGHT (1978)
$N_2(B^3\pi_g)\rightarrow N_2(A^3\Sigma_u^+)+h\nu_{1PG}$	$v'=0$–12, $v''=0$–13	SHEMANSKY and BROADFOOT (1971a)
$N_2(A^3\Sigma_u^+)+O_2\rightarrow N_2+O_2$	$v'=0$–13	PIPER *et al.* (1981a), CARTWRIGHT (1978)
$N_2(A^3\Sigma_u^+)+N_2\rightarrow N_2+N_2$	$v'=0$–13	CARTWRIGHT (1978)
$N_2(A^3\Sigma_u^+)\rightarrow N_2+h\nu_{UK}$	$v'=0$–13	SHEMANSKY (1969)
$N_2(A^3\Sigma_u^+)+O\rightarrow N_2+O(^1S)$	$\beta=0.75$ for $v'=0$–5	CARTWRIGHT (1978), PIPER *et al.* (1981b), PIPER (1982)
$O+e^*\rightarrow O(^1S)+e^*$	Excitation cross section	SHYN *et al.* (1986)
$O(^1S)\rightarrow O(^1D)+h\nu_{5577}$	$A=1.06$	KERNAHAN and PANG (1975)
$O(^1S)+O_2(a^1\Delta_g)\rightarrow O+O_2$	$k=1.7\times10^{-19}$	SLANGER and BLACK (1981)
$O_2(a^1\Delta_g)+N_2\rightarrow O_2+N_2$	$k=1.1\times10^{-19}$	CLARK and WAYNE (1969)
$O_2(a^1\Delta_g)+O_2\rightarrow O_2+O_2$	$k=2.4\times10^{-18}$	CLARK and WAYNE (1969)
$O_2(a^1\Delta_g)\rightarrow O_2(X)+h\nu_{1.27\mu m}$	$A=2.6\times10^{-4}$	BADGER *et al.* (1965)
$O+e^*\rightarrow O(^1D)+e^*$	Excitation cross section	GREEN and STOLARSKI (1972)
$O_2+e^*\rightarrow O_2^++e^*+e$	Ionization cross section	BANKS *et al.* (1974)
$O^++O_2\rightarrow O_2^++O$	$k=3.33\times10^{-12}\cdot\exp(3.72(T/300)^{-1}-1.87(T/300)^{-2})$	CHEN *et al.* (1978)
$N_2^++O_2\rightarrow O_2^++N_2$	$k=5.0\times10^{-11}(T/300)^{-0.8}$	MCFARLAND *et al.* (1973)
$O_2^++e\rightarrow O+O(^1D)$	$\beta=1.2$	ABREU *et al.* (1986)
$O(^1D)\rightarrow O(^3P)+h\nu_{6300}$, $h\nu_{6364}$	$A_{6300}=0.0071$, $A_{6364}=0.0022$	FISCHER and SAHA (1983)
$O(^1D)+N_2\rightarrow O(^3P)+N_2$	$k=2.0\times10^{-11}\cdot\exp(107.8/T)$	STREIT *et al.* (1976)
$O(^1D)+O_2\rightarrow O(^3P)+O_2$	$k=2.9\times10^{-11}\cdot\exp(67.5/T)$	STREIT *et al.* (1976)

A: transition coefficient (s^{-1}), β: branching ratio, k: rate coefficient (cm^{-3} s^{-1}), T: temperature of neutral atmosphere (K)

have been presented by TORR and TORR (1982), and GERDJIKOVA and SHEPHERD (1987). The most possible source of $O(^1S)$ is suggested to be the energy transfer from $N_2(A^3\Sigma_u^+)$: *i.e.*,

$$N_2(A^3\Sigma_u^+)+O \rightarrow N_2(X)+O(^1S) \qquad (1)$$

where the yield of $O(^1S)$ for $v'=0$–5 is inferred from the values measured for $v'=0$ in the laboratory by PIPER (1982). This is the same assumption as that of GERDJIKOVA and SHEPHERD (1987). Our calculation suggests that reaction (1) is the main source of $O(^1S)$ when high energy electrons precipitate into the atmosphere, while the direct electron impact excitation of atomic oxygen becomes the main source of $O(^1S)$ for lower energy electron precipitation.

The chemical reactions for production and loss of $O(^1D)$ are well known. As described by SOLOMON *et al.* (1988), the main contribution to the production of $O(^1D)$ is the direct electron impact excitation of atomic oxygen and the dissociative recombination of O_2^+, while the main loss process of $O(^1D)$ is the quenching by molecular nitrogen and oxygen. We have compared the values obtained from the present model calculation with the result of SOLOMON *et al.* (1988), and have obtained a good agreement between them. We have also compared the emission rates of first positive and Vegard-Kaplan bands of molecular nitrogen calculated by the present method with the airborne observation data of REES *et al.* (1976). The discrepancy between the calculated values and the observed values is within a factor of 2.

3. Results and Discussion

In the present calculation, the incident electron flux $\Psi(E)$ ($cm^{-2}s^{-1}sr^{-1}keV^{-1}$) per unit incident flux ($cm^{-2}s^{-1}$) is assumed to be

$$\Psi(E)=\frac{1}{(2\pi^3)^{1/2}\sigma}\exp\left\{-\frac{(E-E_0)^2}{2\sigma^2}\right\} \qquad (2)$$

where $\sigma=0.1E_0$. This Gaussian type incident flux is the same as that used by BANKS *et al.* (1974). It is also assumed that the peak energy E_0 is 0.5 or 5.0 keV. The top of the atmosphere is taken to be at 500 km.

Figure 2a, b shows the dependence of the altitude profiles of auroral 5577 Å emissions on the thermospheric density variations given in Fig. 1. It is noted that in the case of higher energy electron precipitation, the altitude of the peak emission rate is independent of the density variations of the neutral atmosphere. On the other hand, in the case of lower energy electron precipitation, the peak altitude moves upward by about 20 km when the *Ap* index increases from 4 to 100. This trend is explained by the fact that lower energy electrons interact with the neutral atmosphere at higher altitudes where the density enhancements of N_2 and O_2 caused by increasing magnetic activity are larger than at lower altitudes. The values of the maximum emission rate vary about a factor of 2 in both cases of 0.5 and 5 keV electron precipitation. These variations are due to the variations in the altitude profile of atomic oxygen density.

The dependence of the altitude profile of auroral 6300 Å emissions on the thermo-

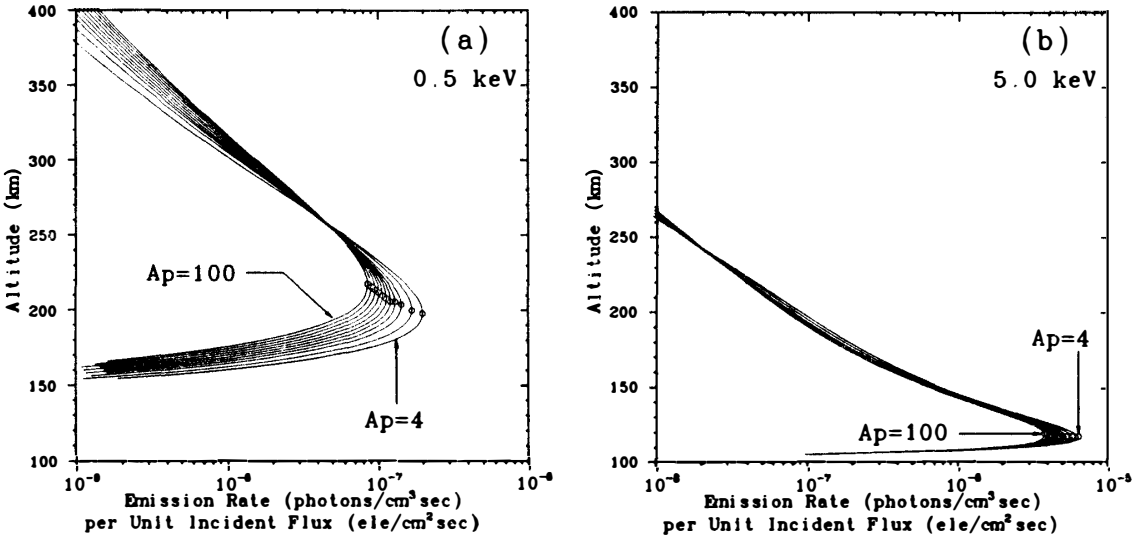

Fig. 2. Altitude profiles of the 5577 Å emission rates for incident electron energy of (a) 0.5 keV and (b) 5.0 keV. The model atmospheres shown in Fig. 1 are used in this calculation. Small circles represent the peaks of the emission rate.

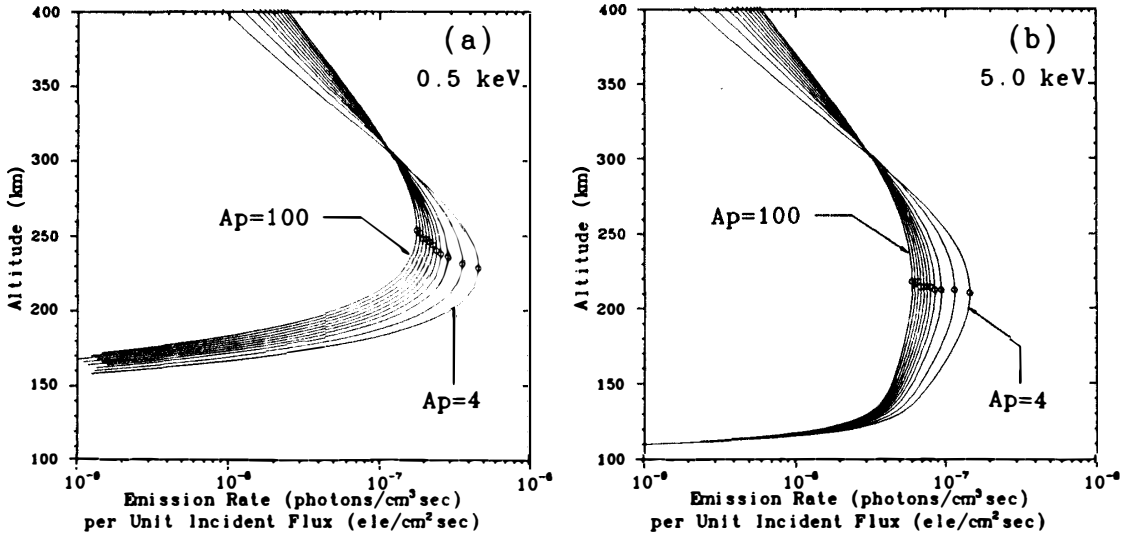

Fig. 3. Altitude profiles of the 6300 Å emission rates. The format is the same as that in Fig. 2.

spheric density variations is shown in Fig. 3a, b. In the case of 5 keV electron precipitation, the altitude profile of emission rate is diffuse due to the strong quenching of $O(^1D)$ by N_2 and O_2. The values of the emission rate vary about a factor of 2.5 in both cases of 0.5 and 5 keV electron precipitation. It seems that this variation is mainly due to the variation of atomic oxygen density profile.

Figure 4a, b show the altitude profiles of the energy deposition rate and their dependences on the density variations of neutral atmosphere associated with magnetic activity changes. The results are similar to those of Fig. 2a, b. However, it is noted that the variation in the peak values of the energy deposition rate is not so large as that of the emission rate, since the energy deposition rate mainly depends on the density

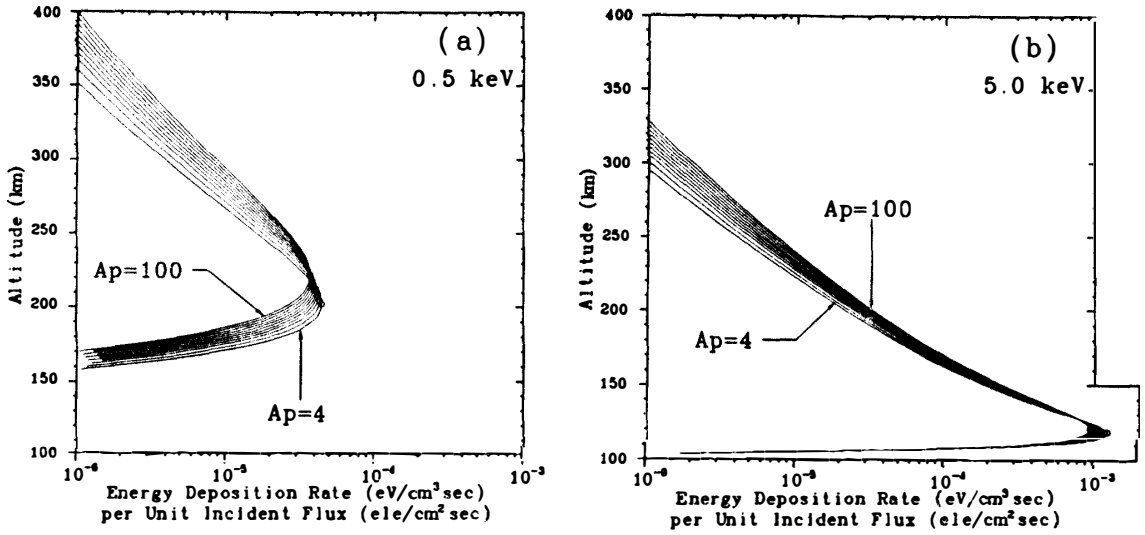

Fig. 4. Altitude profiles of the energy deposition rates. The format is the same as that in Fig. 2.

Table 2. Column emission rate (photons cm^{-2} s^{-1}) and column energy deposition rate (eV cm^{-2} s^{-1}) per unit incident flux (ele cm^{-2} s^{-1}) of 0.5 and 5 keV electrons. Only the maximum and minimum values are displayed when the Ap index is changed from 4 to 100.

	0.5 keV		5.0 keV	
	Minimum	Maximum	Minimum	Maximum
Emission of 5577 Å	0.694 (Ap=100)	1.30 (Ap=4)	10.6 (Ap=100)	15.0 (Ap=4)
Emission of 6300 Å	2.26 (Ap=100)	4.28 (Ap=4)	1.06 (Ap=100)	1.85 (Ap=4)
Energy deposition	309.5 (Ap=4)	314.9 (Ap=100)	3083 (Ap=100)	3090 (Ap=20)

of N_2 and the density variation of N_2 at low altitudes is smaller than that of O as shown in Fig. 1.

Table 2 shows maximum and minimum values in the column emission and energy deposition rates obtained by integrating Figs. 2–4 in the altitude range of 90–500 km. The dependences of 5577 and 6300 Å column emission rates on magnetic activity are mainly due to the variation of atomic oxygen density profile as discussed above. The column energy deposition rate varies slightly, since the density of N_2, which is the main reaction atmospheric constituent in the energy deposition, remains unchanged at lower altitudes.

4. Conclusion

Using the MSIS-86 empirical model developed by HEDIN (1987), we have demonstrated that the rates of auroral 5577 and 6300 Å emissions and energy deposition produced by precipitating electrons vary in association with the density variations in the thermosphere caused by magnetic activity changes. It is shown that the emission rates of 5577 and 6300 Å atomic oxygen lines vary by a factor of 2–3 when the Ap index changes from 4 to 100. It is also shown that the energy deposition rate is slightly dependent on magnetic activity level. In the MSIS-86 model, similar atmospheric

variations are caused by changing the parameter such as geographic location, date and time, and solar $F_{10.7}$ flux. Thus, it is inferred that similar variations in auroral emission and energy deposition rates occur in association with the changes of these parameters. From the above results, we must select these parameters reasonably when we compare observed auroral emissions with calculated ones.

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