JOURNAL OF THE KOREAN ASTRONOMICAL SOCIETY
34: 25~29, 2001

A NON-SPHERICAL MODEL FOR THE HOT OXYGEN CORONA OF MARS

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(Received Feb. 27, 2001; Accepted Mar. 15, 2001)

ABSTRACT

We have constructed a non-spherical model for the hot oxygen corona of Mars by including the effects of planetary rotation and diurnal variation of the Martian ionosphere. Exospheric oxygen densities are calculated by integrating ensemble of ballistic and escaping oxygen atoms from the exobase over the entire planet. The hot oxygen atoms are produced by dissociative recombination of O_2^+, the major ion in the Martian ionosphere. The densities of hot oxygen atoms at the exobase are estimated from electron densities which have been measured to vary with solar zenith angle. Our model shows that the density difference of hot oxygen atoms between noon and terminator is about two orders of magnitude near the exobase, but reduces abruptly around altitudes of 2000 km due to lateral transport. The diurnal variation of hot oxygen densities remains significant up to the altitude of 10000 km. The diurnal variation of the hot oxygen corona should thus be considered when the upcoming Nozomi measurements are analyzed. The non-spherical model of the hot oxygen corona may contribute to building sophisticate solar wind interaction models and thus result in more accurate escaping rate of oxygens from Mars.

Key words: planets: individual (Mars) – planets: atmospheres

I. INTRODUCTION

The oxygen corona of Mars is believed to exist because hot oxygen atoms are produced via dissociative recombination of O_2^+, the major ion in the Martian ionosphere (McElroy 1972). The produced oxygen atoms near the exobase fill in the exosphere and some of them directly escape from Mars. The oxygen escaping flux from the non-thermal process is regarded as an important parameter to constrain the evolution of Martian atmosphere since the Martian oxygens originate mainly from water molecules (eg. Kass & Yung 1995; Jakosky 1991). Hydrogens, the other product of water dissociation, escape efficiently via thermal process even at the cold temperature in the Martian thermosphere (McElory et al. 1977).

The escaping flux and distributions of hot oxygen atoms in the exosphere have been modeled with various methods for calculating production of hot oxygen atoms from the dissociative recombination of O_2^+. The previous models for the hot oxygen corona usually assumed free of collision above the exobase once the energy distribution of hot oxygen atoms is calculated with Monte-Carlo simulation (Ip 1990; Lammer & Bauer 1991) or two-stream transport (Kim et al. 1998). The models also assumed an average condition over the entire globe to calculate a density distribution in one dimension. However, temperatures and densities near the exobase vary by factors of about 2 and 3 over the globe, respectively (Bougher et al. 1999). Moreover, diurnal variation in ionospheric densities has been reported to be at least 100-fold, according to Viking radio occultation measurements (Zhang et al. 1990). Zhang et al. (1993) considered the diurnal variation of the hot oxygen production without including lateral transport from day to night in the coronal distribution. Very recently, Hodges (2000) developed a Monte-Carlo model for the hot oxygen corona by including the diurnal variation of the hot oxygen production, but did not show the density distribution of oxygen around Mars.

In this paper we develop a non-spherical model for the oxygen corona by taking into account the diurnal variation in the hot oxygen production. While observations thus far have not been sensitive enough to detect the oxygen corona, the upcoming Japanese Nozomi mission, schedules to arrive at Mars in 2004, may be able to measure densities of oxygen around Mars. We discuss the effects of non-spherical distribution on solar wind interaction with the Martian exosphere.

II. MODEL

Hot oxygen atoms are generated from dissociative recombination of O_2^+. Branching ratios of dissociation channels have been measured by Kella et al. (1997)

$$(O_2^+ + e) \rightarrow O(^3P) + O(^3P) + 6.99\ \text{eV}(0.22)$$
$$\rightarrow O(^3P) + O(^1D) + 5.02\ \text{eV}(0.42)$$
$$\rightarrow O(^1D) + O(^1D) + 3.06\ \text{eV}(0.31)$$
$$\rightarrow O(^3P) + O(^3S) + 2.80\ \text{eV}(<0.01)$$
$$\rightarrow O(^1D) + O(^1S) + 0.84\ \text{eV}(0.05) \quad (1)$$

where the excess energies and the branching ratios are shown for each channel. The excess energies are shared in the form of kinetic energies of the products, making hot oxygen atoms. The hot oxygen atoms lose their energies via collisions with atmospheric constituents on the way to the exosphere. Kim et al. (1998) simulated the energy loss processes of the hot oxygen atoms through the Martian thermosphere with a two-stream model (Nagy & Banks 1970), and calculated energy distributions of hot oxygen atoms at the exobase altitude. Lammer & Bauer (1991) carried out one-dimensional Monte Carlo simulation for the energy loss pro-cess to approximate the energy distribution as a combination of two Boltzmann distributions of 850 K and 7800 K for a solar minimum case. We adopt these en-ergy distributions, shown in Fig. 1, to derive velocity distributions of hot oxygen atoms at the exobase altitude of 190 km.

The exosphere is so dilute that collision between particles is very rare. In the collisionless space, according to Liouville theorem, the momentum distribution function of particles stays constant along the track of particles (cf. Chamberlain & Hunten 1987). The densities at a position in the exosphere, therefore, can be express-ed with integration of the momentum distribution function at a position on the exobase, where the particles began

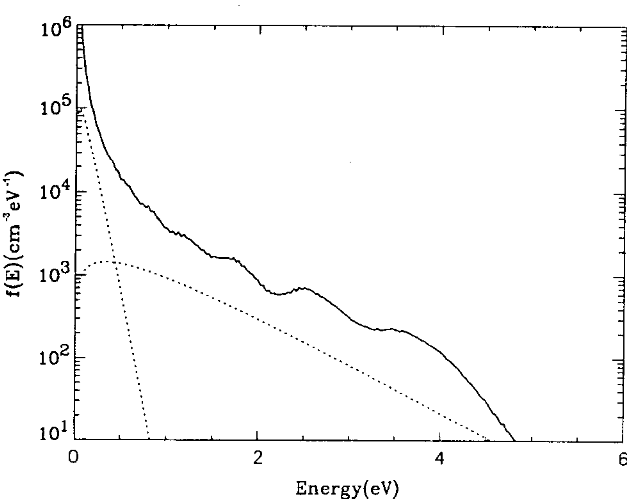

Fig. 1. Energy distributions of hot oxygen atoms at the exobase. Dotted line is adopted from Lammer & Bauer (1991)'s solar minimum case, and solid line is from Kim et al (1998)'s solar maximum case.

orbital motion under the planet's gravity. We developed a code for the integration using Gauss 10 point method, which has been described in detail in Kim & Son (2000). Neither satellite component nor outside source was assumed for the hot oxygen, implying that the hot oxygen corona originates exclusively from the ionosphere below the exobase. This assumption is reasonable because oxygen atoms or ions are very rare in solar wind or interplanetary space.

III. RESULTS AND DISCUSSION

(a) A Uniform Model

We consider first a uniform model for the hot oxygen corona to compare with previous spherical models. Densities of hot oxygen atoms at the exobase were fixed over the globe at 2×10^4 and 10^5 cm^{-3}, which were adopted from Lammer & Bauer (1991)'s solar minimum case and Kim et al. (1998)'s solar maximum case, respectively. The density of hot oxygen atoms can actually be estimated as a volume production rate of hot oxygen atom multiplied by its life time. The life time of the produced oxygen atom can be approximate as time for the oxygen atom to travel scale height, H, with its thermal velocity, v. Therefore, the density of hot oxygen atoms at the exobase may be expressed as

$$N(O) \sim kN(O_2^+)N_2 \times \frac{H}{v} \quad (2)$$

where k is the recombination coefficient for O_2^+. With typical values of $k=10^{-7}$ cm^3s^{-1}, H=100 km, and $v=1$ km/s in the thermosphere, and $N(O_2^+)=N_e=10^5$ cm^{-3}, we obtain a typical hot oxygen density of 10^5 cm^{-3}. At solar minimum, the electron density (and thus ion density) can reduce by half, leading to the hot oxygen den-

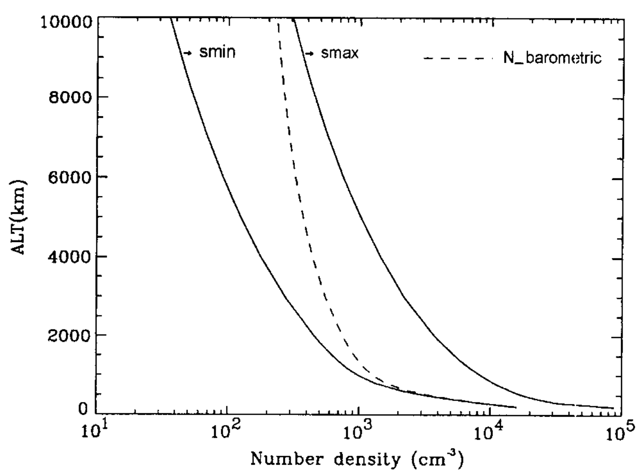

Fig. 2. Density profiles of hot oxygen atoms in the uniform corona model. The solar min and max cases are calculated with energy distributions shown in Fig 1.

sity one quarter of the value for the solar maximum.

The calculated density profiles are shown in Fig. 2 for the solar maximum and minimum cases. The density profiles should be compared with barometric profiles which can be obtained for decreasing gravity and a given temperature if hydrostatic equilibrium were in effect in the collisionless space. The barometric profile is in the form of

$$N(r) = N_c \exp\left(\frac{GMm}{r_c kT_c} + \frac{GMm}{rkT_c}\right) \qquad (3)$$

where N_c, T_c and r_c are density, temperature and planet's radius at the exobase, M and m are masses of the planet and oxygen atom, respectively, and other constants have their usual meanings (cf. Chamberlain & Hunten 1987). For comparion, we only show in Fig. 2 the barometric profile for the solar minimum case, in which the energy distribution has been approximated as a combination of Boltzmann distributions with two temperatures, T_c=850 and 7800 K. The calculated density profile decrease faster than the barometric profile because the velocity distribution of oxygen atoms in practice becomes more directional and its mean kinetic energy decreases as the altitude increases. In other words, the velocity distribution departs from the Boltzmann distribution due to lack of collision in the exosphere.

The densities for the solar maximum and minimum cases differ a factor of about 8 at 6000 km, whereas the assumed density difference at the exobase is 5 times. The slower decrease of the density profile for the solar maximum case is due to the fact that its energy distribution has more energetic portion than the Boltzmann distribution of 7800 K for the solar minimum case. We cannot judge which energy distribution is realistic for the hot oxygen corona until measurements are available. However, the difference may not be of significance since large diurnal variation in production rates of hot oxygen certainly results in non-spherical distribution of the corona, which should appear in measurements.

(b) A Non-spherical Model

The production of hot oxygen atoms is dependent on the densities of O_2^+ and electron, which are virtually the same since O_2^+ is the major ion in the Martian ionosphere. The radio occultation measurements by Viking orbiters show decrease of electron densities with solar zenith angle from the maximum density of about 10^5 cm^{-3} at noon to non-detection at night for solar zenith angles of larger than 95° (Zhang et al. 1990). We approximate the variation of electron density as a cosine function with solar zenith angle (α) as

$$N_e(\alpha) = N(O_2^+)$$
$$= N_{min} + N_{max}\cos\left(\alpha \times \frac{90}{95}\right) \quad \text{if } \alpha < 95^\circ$$
$$= N_{min} \quad \text{if } \alpha > 95^\circ \qquad (4)$$

where $N_{max}=10^5$ cm^{-3} and $N_{min}=10^3$ cm^{-3}, the detection limit of the occultation measurements. Substituting N_e and $N(O_2^+)$ into equation (2) with assumption that all other parameters in (2) are not varying over the globe, we set the densities of hot oxygen atoms at the exobase. Actual densities of hot oxygen atoms are dependent on balance between production rate from O_2^+ ion and loss rate of produced oxygen atoms, which vary not only with solar zenith angles, but also with ionospheric chemistry, diffusion, and other factors over the globe. However, we only consider here the solar zenith angle variation, leaving more sophisticated treatment of boundary condition for hot oxygen in future study.

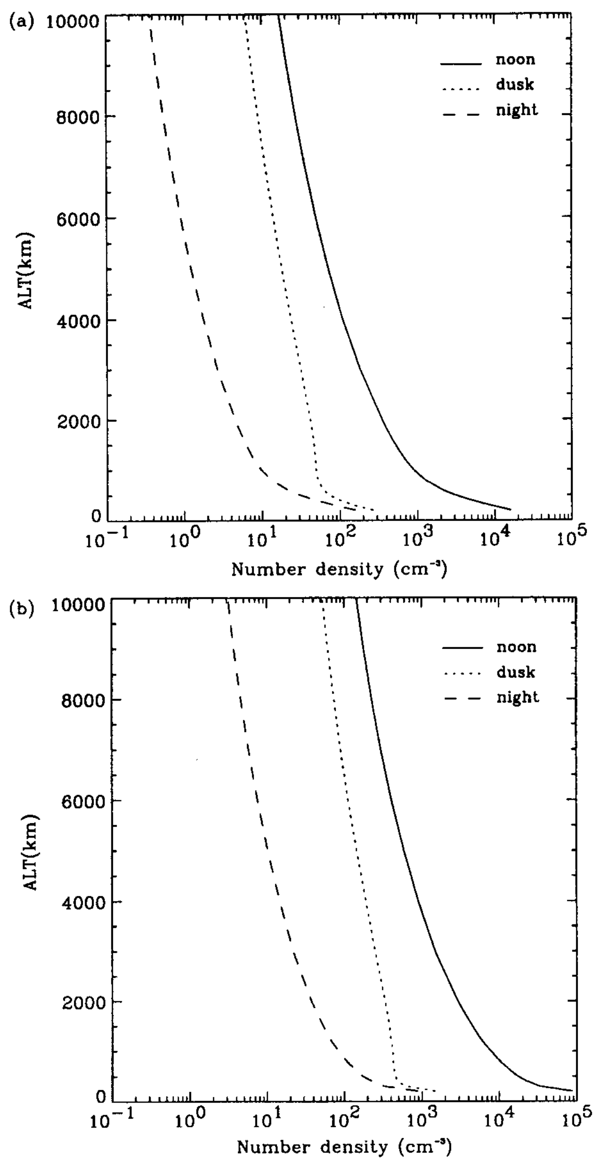

Fig. 3. Density profiles of hot oxygen atoms along noon (solid line), evening or morning (dotted line), and mid-night (dashed line) directions for solar minimum (a) and maximum (b) cases.

Fig. 3 shows density profiles along three directions: noon, terminator, and mid-night. Density profiles along the terminator direction are very different from others, showing sharp decrease up to 500 km, a little increase up to 1500 km, and mild decrease at higher altitudes. Hot oxygen atoms are produced very little in the night side, but are transferred from the day side very efficiently along ballistic trajectory to fill the densities above 500 km. The density profiles for the solar maximum case are larger by about 10 times than the corresponding profiles for the solar minimum case, but their shapes are similar each other. The density difference between noon and terminator is 60 times at the exobase, but decreases to 3 times at an altitude of 10000 km. The density variation will continue to decrease with altitude because densities at the higher altitudes are determined from production of hot oxygen atoms over the wider area of the planet, and thus reflect average value over the wider area.

The variation can be seen more graphically in Fig. 4, where density distributions on the equatorial plane are shown in gray scales. The density distributions near the terminators are enhanced significantly by lateral transport of hot oxygen atoms from the day side. The distribution in the night hemisphere is, however, very uncertain due to non-detection of the night-side ionosphere. The distribution is symmetric with respect to the noon to mid-night line because the condition at the exobase was assumed to be dependent only on solar zenith angle. Planet's rotation affects very little the density distribution, although the rotational speed has been added to the ballistic speed of hot oxygen atoms leaving the exobase.

The non-spherical model constructed here should be more adequate than previous spherical models to be compared with upcoming Nozomi measurements in the Martian exosphere. Since energy distributions and densities of hot oxygen atoms are uncertain at the exobase, the Nozomi measurements can provide information on these boundary conditions when compared with our non-spherical model.

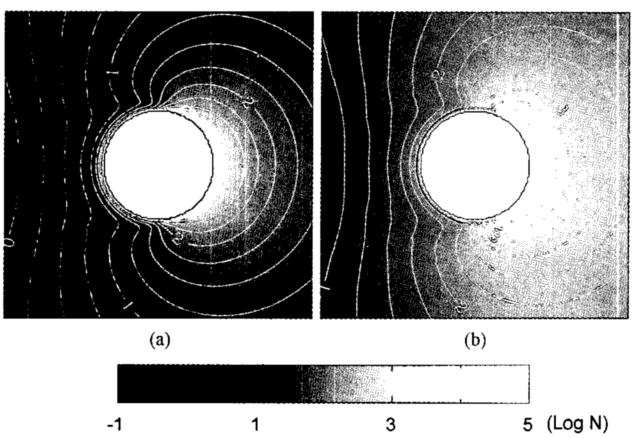

Fig. 4. Density distribution of hot oxygen atoms on the equatorial plane for solar minimum (a) and maximum (b) cases. The right and up directions are noon and evening meridians, respectively.

The shape of the hot oxygen corona in Fig. 4 is very non-spherical, having maximum densities at noon and minimum at mid-night. We test whether the non-spherical shape of the hot oxygen corona may cause in any significant effect in solar wind interaction with the Martian exosphere. For the test, the Martian exosphere was constructed by adding our non-spherical model of the hot oxygen corona to a standard spherical model of hydrogen atoms and molecules. The interaction of a standard solar wind with the modified exosphere model was simulated with a magnetohydrodymic (MHD) code (Yi et al. 1999). The simulation shows no significant change in bow shock location due to the non-spherical shape of the added hot oxygen corona. This is because hydrogen atoms and molecules, whose densities are much larger than those of hot oxygen atoms in the Martian exosphere, are too dominant for the solar wind interaction. However, more sophisticate interaction models, for example multi-component MHD models or kinetic interaction models, may appreciate the non-spherical shape of the hot oxygen corona, and thus lead to more accurate calculation for escaping rate of oxygen by solar wind interaction. The escape rate of oxygen is an important parameter for understanding the evolution of Martian atmosphere (eg. Kass & Yung 1995; Jakosky 1991).

IV. CONCLUSION

We have constructed a non-spherical model for the hot oxygen corona around Mars by integrating velocity functions at the exobase, with assumption that above the exobase particles move collisionlessly on a ballistic and hyperbolic orbit under the planet's gravity. The hot oxygen atoms are produced by dissociative recombination of O_2^+, the major ion in the Martian ionosphere. The densities of hot oxygen atoms at the exobase are estimated from electron densities which have been measured to vary with solar zenith angle. The model shows that the density difference of hot oxygen atoms between noon and terminator is about two orders of magnitude near the exobase, but reduces abruptly around altitudes of 2000 km due to lateral transport. The diurnal variation of hot oxygen densities remains significant up to the altitude of 10000 km. Although the non-spherical shape of the hot oxygen corona does not affect significantly a simple MHD model of solar wind interaction with the Martian exosphere, it will contribute to more sophisticate solar wind interaction models and thus will result in more accurate escaping rate of oxygens from Mars. The non-spherical model of the hot oxygen corona is also more adequate than previous spherical models to be compared with the upcoming Nozomi measurements.

YHK acknowledges the financial support of the Korea Science and Engineering Foundation (1999-1-113-001-5).

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