Chin. J. Astron. Astrophys. Vol. 1, No. 2, (2001) 185–189
(*http://www.chjaa.org* or *http://chjaa.bao.ac.cn*)

Chinese Journal of
Astronomy and
Astrophysics

The O^+ Ion Flux in the Martian Magnetosphere and Martian Intrinsic Moment

Jian-Kui Shi[1]*, Zhen-Xing Liu[1] and T. L. Zchang[2]

[1] Center for Space Science and Applied Research, Chinese Academy of Sciences, Beijing 100080
[2] Space Research Institute, Austrian Academy of Sciences, Inffeldgasse 12, A-8010 Graz, Austria

Received 2000 July 4; accepted 2001 January 6

Abstract A model is developed to study the ionospheric ion flux distribution along magnetic force lines in Martian magnetosphere and the influence of Martian intrinsic moment on the distribution. It is discovered that the intrinsic moment has significant influence on the O^+ ion flux distribution that a lower flux in the magnetotail will be associated with a stronger intrinsic moment. According to the theoretical result and the observed data on the ion flux which is about 7.6×10^6 cm^{-2} s^{-1} in the Martian magnetotail, the deduced Martian moment is about 2×10^{21} G cm^3. This agrees well with the most recent data obtained by MAG/ER on the Mars Global Surveyor spacecraft.

Key words: Planets and satellites: individual: Mars

1 INTRODUCTION

The early observations revealed evidence for an intrinsic magnetic field on Mars (Gallagher & Simpson 1965). At larger Mars-centric distance on the night side, the Martian magnetic field is mainly an induced field due to the interaction of the solar wind with Mars (Riedler et al. 1991). According to the analysis of experimental data obtained by different earlier spacecraft, the dipole intrinsic moment of Mars ranges from about 2×10^{21} G cm^3 (Russell 1978; Acuna et al. 1998) to about 2×10^{22} G cm^3 (O'Gringauz 1991). More recent data obtained by MAG/ER on the Mars Global Surveyor (MGS) spacecraft show an upper limit for a Mars dipole moment of $\sim 2 \times 10^{21}$ G cm^3, about a factor of 5 or 10 smaller than the estimates derived from the spacecraft Phobos data. And the accuracy is limited by the spacecraft field (Acuna et al. 1998). So, the question of the structure of the magnetosphere and the dipole moment of Mars remains open.

Analysis of the experimental data shows that the magnetotail of Mars is composed of H^+ and O^+ ions which are basically of ionospheric origin (Rosenbauer et al. 1989). The plasmasheet is mainly formed by O^+ ions and its mean flux is about $7\times10^6 \sim 8\times10^6$ cm^{-2} s^{-1} (Lundin et al. 1989). Lammer and Bauer (1992) used plasma mantle mechanism to calculate the flux of

---

$\star$ E-mail: jkshi@center.cssar.ac.cn

escaping heavy ions. Haider (1995) used the polar wind mechanism to calculate the escape flux of O^+ ions through the plasmasheet at different exospheric temperatures along magnetic field lines originating from the baropause.

In the present study, the distribution function obtained by solving the dynamic equation of the ions is used to calculate the O^+ ion flux along the field line starting from the ion exobase for different assumed values of Martian intrinsic moment. It is found that the ion distribution depends on the intrinsic moment. According to our model and the observations of the ion flux, the Martian intrinsic moment deduced from the ion distribution is about 2×10^{21} G cm^3. This is consistent with the most recent observation from the MGS Spacecraft.

2 PHYSICAL MODEL

We consider ions moving in the exosphere above the base S_0. The guiding center approach is valid because collision can be ignored in the exosphere (Eviater et al. 1964). We also suppose the following conditions are satisfied above the base S_0: (1) Quasi-neutrality holds everywhere in the region. (2) The ion gyration radius and gyration period are much smaller than the characteristic distance and the characteristic time of field variation, respectively. The ion distribution function $F(t, \boldsymbol{R}, v)$ satisfies

$$\frac{\partial F}{\partial t} + \nabla_R \cdot (F\boldsymbol{v}) + \nabla_v \cdot (F\dot{\boldsymbol{v}}) = 0 \ , \tag{1}$$

where t is the time, R the instantaneous position of the ion, and $v = \mathrm{d}\boldsymbol{R}/\mathrm{d}t$ the ion velocity, $\dot{\boldsymbol{v}} = \mathrm{d}\boldsymbol{v}/\mathrm{d}t$. Let $\boldsymbol{r}$ be the position of the guiding center; then $\boldsymbol{R} = \boldsymbol{r} + \rho$ (ρ is the ion gyration radius), and $\boldsymbol{v} = \boldsymbol{u} + \boldsymbol{v}_\mathrm{d}$ ($\boldsymbol{v}_\mathrm{d}$ is the ion drift velocity). Considering $\boldsymbol{v}_\mathrm{d} \ll \boldsymbol{v}$, substituting the expanded forms of the operators ∇_R and ∇_v at the point $(\boldsymbol{r}, \boldsymbol{u})$ in phase space into Eq. (1), comparing the orders of magnitude and averaging them over the period of the ion gyration, Eq.(1) can be rewritten as

$$\frac{\partial F}{\partial t} + \nabla_r \cdot (F\dot{\boldsymbol{r}}) + \nabla_u \cdot (F\dot{\boldsymbol{u}}) = 0 \ , \tag{2}$$

where $F = (F\boldsymbol{r}, \boldsymbol{u}, t)$, $\dot{\boldsymbol{r}} = \mathrm{d}\boldsymbol{r}/\mathrm{d}t$, $\dot{\boldsymbol{u}} = \mathrm{d}\boldsymbol{u}/\mathrm{d}t$. Consider a magnetic tube of force (field lines mentioned in this paper always refer to lines along the tube axis). Let $f(s, \boldsymbol{u}, t)$ be the integration of F over the cross section of the tube, s the coordinate along the field line. Then, $f(s, \boldsymbol{u}, t)$ is, at time t and at point $(s, \boldsymbol{u})$, the number of guiding centers per unit length of the tube and unit time interval. We assume the transport of ionospheric ions moving along the field line takes place during a period of magnetic quiet or slow variation, so the ions conserve magnetic moment and energy. Starting from Eqs.(2) and (3), we consider the static problem and obtain the static equation (Eviater et al. 1964).

$$u_\parallel \frac{\partial f}{\partial s} + \frac{u_\perp u_\parallel}{2B}\frac{\partial B}{\partial s}\frac{\partial f}{\partial u_\perp} - \left(\frac{u_\perp^2}{2B}\frac{\partial B}{\partial s} + \frac{1}{M}\frac{\partial \Phi}{\partial s}\right)\frac{\partial f}{\partial u_\parallel} = 0\,, \tag{3}$$

where $f = f(s, u_\parallel, u_\perp)$, $u_\parallel$, $u_\perp$ are the components of $\boldsymbol{u}$ parallel and perpendicular to the field lines, respectively. B is the magnetic field, M ion mass, and Φ the sum of the gravity potential and electrical potential. The subscript “0” denotes quantities at the base S_0.

Because the ions originating in Martian ionosphere are accelerated in the region below the base S_0 (somewhat as in the case of the Earth) and move upward along the field line, the ion distribution function at the boundary (at the base S_0) can be taken as

$$f(s_0, u_\parallel, u_\perp) = \begin{cases} C\exp\left(-\frac{\frac{1}{2}M(u_\parallel^2+u_\perp^2)-E_0}{T}\right), & (\theta < \theta_0, E > E_0) \\ 0\,, & \text{(other)} \end{cases} \tag{4}$$

where θ is the ion pitch angle, T the ion temperature parameter, $E = 1/2M\left(u_\parallel^2 + u_\perp^2\right)$, E_0, θ_0 and C are constants.

The solution of Eq.(3) satisfying the boundary function (4) is found to be

$$f(s_0, u_\parallel, u_\perp) = \begin{cases} C\exp\left(-\frac{\frac{1}{2}M(u_\parallel^2+u_\perp^2)-E_0+\Phi}{T}\right), & (\theta < \theta_m, E > E_m) \\ 0\,, & \text{(other)} \end{cases} \tag{5}$$

where θ_m is the maximum ion pitch angle at point s, $E_m = E_0 - \Phi$. Regarding that θ_m is small, we have $u_\parallel \ll u_\perp$.

Considering the conservation of magnetic flux, the normalized ion flux along the field line (the ratio between the fluxes at point s and at the base S_0) can be written as

$$\mathrm{Flux}(s) = \frac{B \cdot \iint_U u_\parallel f\left(s, u_\parallel, u_\perp\right) u_\perp \mathrm{d}u_\parallel \mathrm{d}u_\perp}{B_0 \cdot \iint_U u_\parallel f\left(s_0, u_\parallel, u_\perp\right) u_\perp \mathrm{d}u_\parallel \mathrm{d}u_\perp}\,, \tag{6}$$

where U is the area: $\theta < \theta_m$, $E > E_m$ in phase space $u_\parallel - u_\perp$.

Using Eq.(6) and the ion flux at the base, the flux distribution along the force line at any point can be calculated.

3 RESULTS AND DISCUSSION

With reference to the Earth's magnetosphere, we take the Martian magnetic field to consist of an intrinsic field and an induced field (Lammer & Bauer 1992), the latter is duo to the interaction of the solar wind and Mars. The induced field B_T is taken as 10 nT (Luhmann & Brace 1991; Slavin & Holzer 1982). Let m be the Martian dipole moment, the Mars-centric distance of S_0 be $1.1R_m$, (R_m being the radius of Mars), $T = 2000\,$K, and $E_0 = 2.5\,$eV, the parallel electric field (Lammer and Bauer 1992) $E_e = 1\,\mu$ V/m. According to the observations, the O$^+$ ion flux is taken as $2{\times}10^7\,\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ (Verigin 1991) at the base S_0. We consider the meridian plane and use Eq. (6) for the calculation.

Figure 1 illustrates the O$^+$ ion flux distributions along the same field line at co-latitude 15° for different assumed values of the dipole intrinsic moment. The induced magnetic field B_T is taken as 10 nT in the calculation. In Figure 1, the curves, from top to down, correspond to dipole moment $m = 1, 1.5, 2, 3$, and $5{\times}10^{21}$ G cm^3. From Figure 1, we can see that the ion flux in the Martian magnetosphere decreases with increasing distance from the planet, and decreases more quickly in the near-Mars space than further out. We also can see that, when the intrinsic moment $m = 1{\times}10^{21}$ G cm^3, the flux of O$^+$ ion along the field line decreases slowly to a level of about $1.1{\times}10^7\,\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ at distance $2.8\,R_m$ in the magnetotail. For a moment $m = 1.5{\times}10^{21}$ G cm^3, the flux of O$^+$ ion along the field line decreases quickly and reaches a level of about $0.9{\times}10^7\,\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ at distance $2.8\,R_m$ in the magnetotail. The decrease is more pronounced for larger moments, the level are about $0.76{\times}10^7\,\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$, $0.58{\times}10^7\,\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$, and $0.26{\times}10^7\,\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$, for $m = 2$, 3, and $5{\times}10^{21}$ G cm^3 at distance $2.8\,R_m$ in the magnetotail, respectively. Therefore, the moment does have an influence on the ion flux distribution along the field lines. The stronger the moment is, the more quickly the O$^+$ ion flux will decrease along the field lines with increasing distance from the planet, and the lower the O$^+$ ion flux level in the magnetotail will be.

Figure 2 shows that the variation of the ion flux with Martian magnetic moment along the field line at co-latitude 15° at the distance of $2.8\,R_m$ in Martian magnetotail. From Figure 2, we can see clearly that O$^+$ ion flux decreases with increasing magnetic moment.

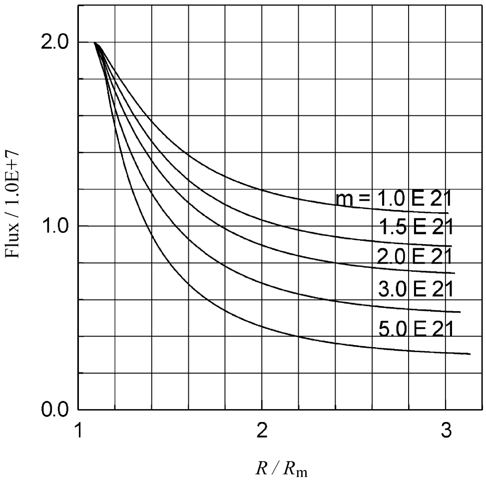

Fig. 1 The O$^+$ flux along the field line of co-latitude $\lambda = 15°$ for different dipole moments, induced magnetic field $B_T = 10\,\mathrm{nT}$, and parallel electric field $E_e = 1\ \mu\mathrm{V/m}$.

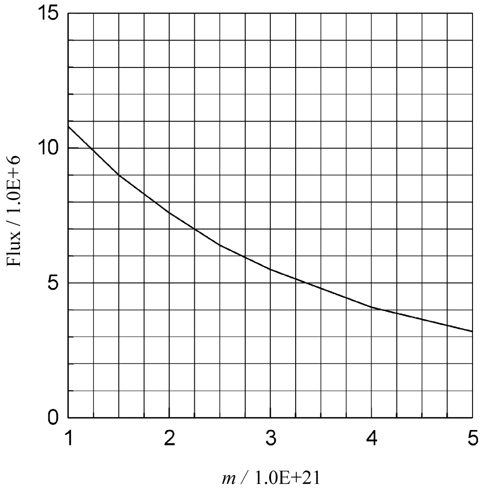

Fig. 2 The O$^+$ ion flux versus the moment at distance $2.8\,R_M$ for co-latitude $\lambda = 15°$, induced magnetic field $B_T = 10\,\mathrm{nT}$, and parallel electric field $E_e = 1\mu\,\mathrm{V/m}$.

According to the observations, the mean flux of O$^+$ ion is about $7 \sim 8 \times 10^6\,\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ in the Martian magnetosheet (Lundin 1989) and the most recent observed value of the Martian moment is about $2{\times}10^{21}\,\mathrm{G\,cm}^3$ (Acuna et al. 1998). From Figures 1 and 2, we can see that if the O$^+$ ion flux is about $7.6{\times}10^6\,\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ in the magnetosheet, the Martian intrinsic moment will be $2{\times}10^{21}\,\mathrm{G\,cm}^3$. Surprisingly, this result is quite consistent with the observation. So, our theoretical result suggests that the Martian dipole moment would also be about $2{\times}10^{21}\,\mathrm{G\,cm}^3$ which is consistent with the recent observed result obtained from the MGS spacecraft.

Using the values of the induced magnetic field $B_T = 10\,\mathrm{nT}$ (Lammer & Bauer 1992) and of the Martian dipole intrinsic moment $m = 2{\times}10^{21}\,\mathrm{G\,cm}^3$ suggested by our theoretical result, we can calculate the intensity of Martian magnetic field. Figure 3 (a) illustrates the intensity of Martian magnetic field along orbit 2 of the Phobos 2 spacecraft observed in February, 1989 (Dolginov & Zhuzgov 1991; Riedler et al. 1989). Figure 3 (b) shows our theoretical result when a Martian dipole moment $m = 2{\times}10^{21}\ \mathrm{G\ cm}^3$ and a tail-like induced magnetic field $B_T = 10\,\mathrm{nT}$ are taken into account. From Fig. 3 it can be seen that our theoretical result agrees well with the observation.

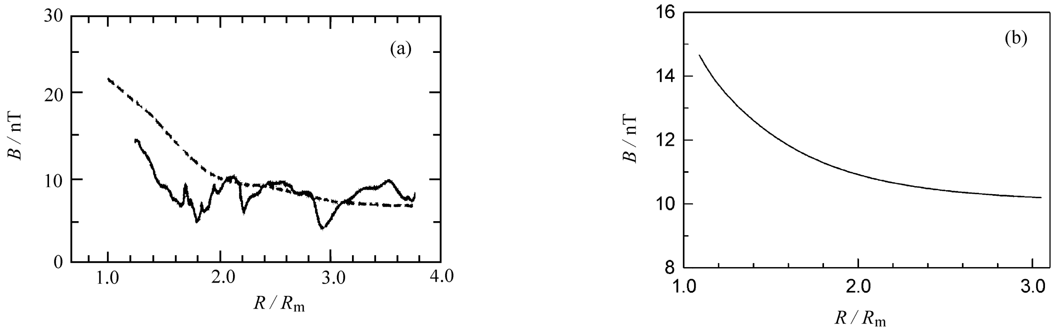

Fig. 3 The intensity of Martian magnetic field along orbit 2 of the Phobos 2 spacecraft. (a) the observed result (Dolginov & Zhuzgov 1991), and (b) the theoretical result calculated by our model.

4 SUMMARY

In this paper, taking the Martian magnetic field as a superposition of a dipole intrinsic field and a tail-like induced field (Luhmann & Brace, 1991) due to the interaction of the solar wind and Mars, we develop a model to study the ionospheric ion flux distribution along the force lines in the Martian ionosphere and the influence of the intrinsic moment on the ion distribution. The results are as follows.

(1) The intrinsic moment has an influence on the O^+ ion flux distribution, a lower flux in the magnetotail being associated with a stronger intrinsic moment.

(2) From the observed data on O^+ ion flux of about $7.6\times10^6\,\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ in the Martian magnetotail, we deduce the Martian moment to be about 2×10^{21} G cm^3. This agrees well with the most recent data obtained by MAG/ER onboard the Mars Global Surveyor spacecraft.

Acknowledgements This research work is supported by National Nature Science Foundation of China under grant No. 49884002.

References

Acuna M. H., Connerney J. E. P., Wasilewski P. et al., 1998, Science, 279, 1676
Dolginov S. S., Zhuzgov L. N., 1991, Planet Space Sci., 39, 1493
Eviater A., Lencheek A. M., Singer S. F., 1964, Phys. Fluids, 7, 1775
Gallagher J. J., Simpson J. A., 1965, Science, 149, 1233
Haider S. A., 1995, Adv. Space Res., 16, 49
Lammer H., Bauer S. J., 1992, J. Geophys. Res., 97, 20925
Luhmann J. G., Brace L. H., 1991, Rev. Geophys., 29, 121
Lundin R., et al., 1989, Nature, 341, 609
O'Gringauz K. I., 1991, Planet Space Sci., 39, 73
Riedler W. et al., 1991, Planet Space Sci., 39, 75
Riedler W., Schwingenschuh K. et al., 1989, Nature, 341, 604
Rosenbauer H. et al., 1989, Nature, 341, 612
Russell C. T., 1978, Geophys. Res. Lett., 5, 81
Slavin J. V., Holzer R. E., 1982, J. Geophys. Res., 87, 10285
Verigin M. I. et al., 1991, Planet Space Sci., 39, 131