

Solar wind interaction with Mars

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The existence of intrinsic magnetic field at Mars is still a subject of debate. The ionospheric thermal pressure above 300 km is insufficient by itself to withstand the solar wind dynamic pressure, suggesting the presence of magnetic field in the ionosphere of Mars which can either be a weak intrinsic magnetic field or an induced magnetic field driven by solar wind interaction with Mars. The photodynamical model of Mahajan and Mayr [*J Geophys Res (USA)*, 95 (1990) 8265] for the case of magnetic field induced by solar wind plus ion loss via horizontal convection has been studied. It has been found that the induced magnetic field does not affect or alter the photodynamical nature of the ionosphere of Mars.

1 Introduction

The existence of intrinsic magnetic field at Mars is still a subject of debate. The ion densities, measured in the ionosphere of Mars above 300 km by retarding potential analyser (RPA) on the Viking landers, are very low¹. The ionospheric thermal pressure above 300 km is not sufficient by itself to balance the solar wind dynamic pressure, suggesting the presence of a magnetic field in the ionosphere of Mars². In fact, the ionospheric thermal pressure near 300 km is exceeded by the typical solar wind dynamic pressure 85% of the time³. Therefore, either an intrinsic or an induced magnetic field must exist in the ionosphere of Mars. Some investigators found the evidence of intrinsic magnetic field at Mars from the magnetic field measurements made by Mariner-2, 3, 4 and 5 spacecrafts in the Martian magnetosheath region.

Using an electrodynamic model, Cloutier and Daniell⁴ suggested that the upper ionosphere (altitude greater than 250 km) is dominated by solar wind-driven convective motion, implying that the intrinsic magnetic field on Mars is insignificant and is less than 25 nT on the surface. Shinagawa and Cravens⁵ produced a one-dimensional multi-species magnetohydrodynamic model of the Martian ionosphere and concluded that the intrinsic magnetic field of Mars is very small and does not play any major role in solar wind interaction.

Mahajan and Mayr⁶ presented a photodynamical model of Martian ionosphere and have shown that the O_2^+ profiles measured by the Viking landers are quite different from those expected under diffusive equilibrium. They have inferred that the O_2^+ profiles, which form the major portion of the ionosphere of Mars up to 300 km, are disturbed due to horizontal and vertical flows induced by solar wind. They have further argued that these profiles can produce a photodynamical ionopause at about 350 km, the altitude where the ion density falls to $100/\text{cm}^3$, a definition used by Brace *et al.*⁷ for Venus ionopause. Their final conclusion is that the solar wind interacts directly with the ionosphere of Mars and the planet does not have an intrinsic magnetic field of any consequence.

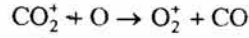
One of the most intriguing results from the plasma instruments aboard the spacecraft Phobos-2 was the *in situ* observation of a massive plasma escape through the magnetotail region of Mars. Shinagawa and Cravens⁵ invoked a large scale convection to reach an agreement between observed ion densities and their one dimensional magnetohydrodynamic model of the Martian ionosphere having large scale induced magnetic fields.

In the present paper, we have considered the photodynamical model of the Martian ionosphere given by Mahajan and Mayr⁶ and presented the

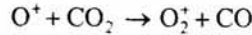
results of studies for the case of loss of ions due to divergence of horizontal ion velocities.

2 Formulation

The ionosphere of Mars is formed by the photoionization of major neutral constituents CO_2 , O_2 , and O . The following reactions produce O_2^+ as major species of F1 layer:



and



The molecular ions are destroyed by dissociative recombination. For such an ionosphere, the chemical and diffusion time constants of O_2^+ are given by

$$T_c = \frac{1}{\alpha [\text{O}_2^+]} \quad \dots (1)$$

$$T_D = H_D^2 m_i v_m / k(T_e + T_i) \quad \dots (2)$$

where T_c is the chemical time constant, α the dissociative recombination coefficient of O_2^+ [taken as $1.6 \times 10^{-7} (300/T)^{0.55} \text{ cm}^3 \text{ s}^{-1}$], T_D the diffusion time constant, H_D the scale height of CO_2 , m_i the mass of ion, v_m the ion-neutral collision frequency, T_e the electron temperature, and T_i the ion temperature. The expression for v_m is given by

$$v_m = 2.6 \times 10^{-9} n(n)(\alpha_0/\mu_A)^{1/2} \text{ s}^{-1} \quad \dots (3)$$

where α_0 is the atomic polarizability in units of 10^{-24} cm^3 (2.6 for CO_2), μ_A the reduced atomic mass, and $n(n)$ the number density of neutral constituents.

It has been found from the calculations of Mahajan and Mayr⁶ that diffusion becomes important above 160 km. In the photodynamical regime, the chemical process can be neglected and continuity equation becomes:

$$W \frac{\partial N_i}{\partial z} + N_i \frac{\partial W}{\partial z} + U \frac{\partial N_i}{\partial y} + N_i \frac{\partial U}{\partial y} = Q_i \quad \dots (4)$$

where N_i is the number density of O_2^+ ions, W and U are vertical and horizontal ion transport velocities imparted by solar wind, Q_i is the ion production rate of O_2^+ , and y and z are the horizontal and vertical coordinates.

To study the first-order behaviour of photodynamical regime, Mahajan and Mayr⁶ made following assumptions: (1) horizontal gradient of ion density is zero, and (2) vertical velocity varies

slowly with altitude so that the scale height of W is larger than that of N_i .

It is supposed by us that the gradient of horizontal transport velocity is caused due to the induced magnetic field. The velocity remains constant in the absence of induced magnetic field.

Under these assumptions, the continuity Eq. (4) reduces to

$$N_i(z) \left[\frac{\partial U}{\partial y} - \frac{W}{H(Q_i)} \right] = Q_i(z) \quad \dots (5)$$

Shinagawa and Cravens⁵ found the best agreement between their theoretical model and the observation for the case of purely induced magnetic field plus ion loss via horizontal convection. They gave the estimated horizontal divergence by

$$\frac{\partial U}{\partial y} = \frac{v_{in}}{2} \left[-1 + \left(1 + \frac{4B^2 / \mu_0}{m_i n_e v_{in}^2 R_M^2} \right)^{1/2} \right] \quad \dots (6)$$

where B is the induced magnetic field, n_e the electron density, and R_M the distance between the centre of Mars and the ionosphere.

Coupling Eqs (5) and (6) together, we have presented the altitude profiles of ion production rate of O_2^+ in Figs 1 and 2 for Viking-1 and Viking-2 respectively. For Viking-1, Q_i (solid line) in Fig. 1 represents the case of Mahajan and Mayr⁶ for the downward velocity of 150 ms^{-1} when there is no induced magnetic field on Mars, and Q_i [dotted lines (1) and (2)] for downward velocities 150 ms^{-1} and 200 ms^{-1} respectively when there is induced magnetic field. Similarly for Viking-2, Q_i (solid line) in Fig. 2 represents the case of Mahajan and Mayr⁶ for the downward velocity of 175 ms^{-1} when there is no induced magnetic field on Mars, and Q_i [dotted lines (1) and (2)] for downward velocities of 175 ms^{-1} and 225 ms^{-1} respectively when there is induced magnetic field. Altitude profile of ion loss rate is shown in Fig. 3. We have used the altitude profile of magnetic field strength as calculated by Shinagawa and Cravens⁵ and the scale height for Q_i obtained by Mahajan and Mayr⁶. The magnetic field has been assumed to be horizontal⁵ (Fig. 4).

3 Discussion

It can be seen from Figs 1 and 2 that the observed O_2^+ profile above about 160 km on Mars

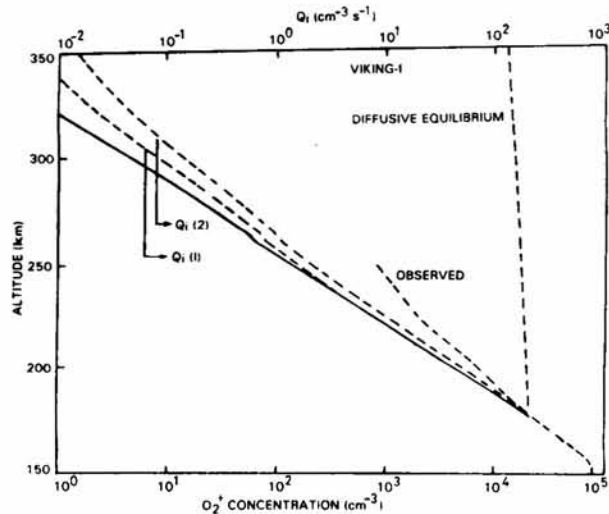


Fig. 1—Altitude profiles of the ion production rate Q_i are shown for Viking-1. The solid line represents the non-magnetic case for a downward velocity of 150 ms^{-1} . The dotted lines (1) and (2) represent the magnetic cases for downward velocities of 150 ms^{-1} and 200 ms^{-1} .

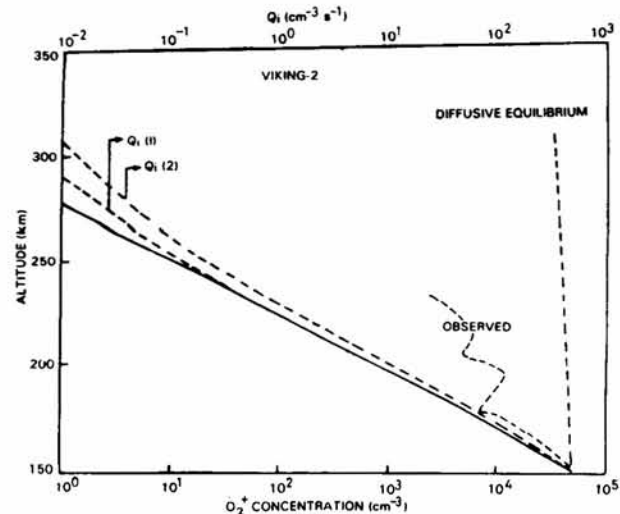


Fig. 2—Altitude profiles of the ion production rate Q_i are shown for Viking-2. The solid line represents the non-magnetic case for a downward velocity of 175 ms^{-1} . The dotted lines (1) and (2) represent the magnetic cases for downward velocities of 175 ms^{-1} and 225 ms^{-1} .

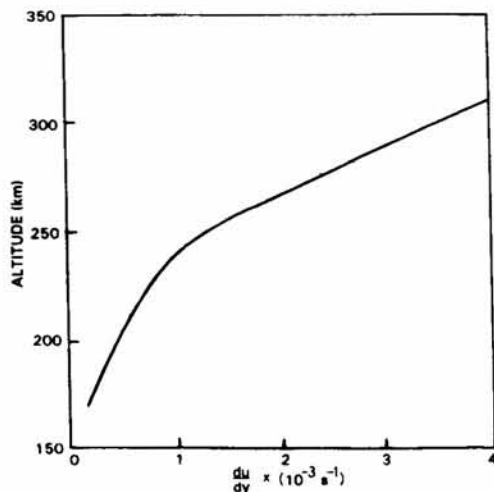


Fig. 3—Altitude profile of ion loss rate.

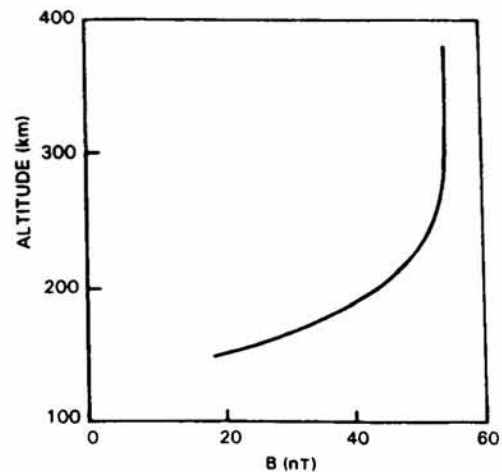


Fig. 4—Altitude profile of magnetic field strength (after Shinagawa and Cravens⁵).

is a disturbed ionosphere with an ionopause around at 325 km. Following Mahajan and Mayr⁶, it can be inferred that the observed O_2^+ profile follows Q_i profile (solid line) below 240 km for downward velocities of 150 ms^{-1} for Viking-1 and 175 ms^{-1} for Viking-2. With the same downward velocities, the induced magnetic field generates greater Q_i [dotted line (1)] that follows observed O_2^+ profile above 240 km. This is owing to the fact that in the high altitude magnetized region, ions are removed by horizontal transport because the loss rate is approximately proportional to the magnitude of

magnetic field [see Eq. (6)]. Below 240 km, the horizontal transport is inhibited by the ion-neutral drag as the ion loss rate is inversely proportional to the ion-neutral collision frequency. Mahajan and Mayr⁶ have discussed in their model the magnitude of downward velocities consistent with the ion density profile. They have found the downward velocities to be ranging anywhere in between 150 and 10 ms^{-1} in altitude from 150 km to 250 km for Viking-1 and similar values for Viking-2. Referring to Figs 1 and 2 again, with the downward velocities of 200 ms^{-1} for Viking-1 and

225 ms^{-1} for Viking-2, the induced magnetic field produces Q_i profiles [dotted lines (2)] that follow observed O_2^+ profiles more closely around 240 km of altitude. We have shown in Fig. 3 the altitude profile of ion loss rate. The ion loss rate becomes significant above 250 km and increases smoothly with altitude, reaching about $4 \times 10^3 \text{ s}^{-1}$ in the topside of ionosphere. From the comparison of scale height of observed ion distribution/ion production rate with diffusive scale height, Mahajan and Mayr⁶ have shown that the ionosphere in the photodynamical region above 150 km is disturbed by the solar wind interaction, forming the photodynamical ionopause. For the magnetic case, we have measured the scale heights for Q_i from Figs 1 and 2 and found them to be almost equal to those obtained by Mahajan and Mayr⁶. This shows that, even in the presence of induced magnetic field, the ionosphere in the photodynamical region remains disturbed by solar wind interaction.

4 Conclusions

We have examined the Mahajan and Mayr model⁶ for the case of purely induced magnetic field plus ion loss via horizontal convection. The

results demonstrate that the horizontal transport is a key process in removing ionospheric plasma at high altitude. It also appears from the results that the induced magnetic field remains disturbed and does not affect or alter the photodynamical nature of the ionosphere of Mars.

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