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On the effects of the Martian crustal magnetic field on atmospheric erosion

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Abstract

While there is a perception that the Martian magnetic anomalies are significant for the ionospheric density distribution and the bow shock standoff location, little is known about the quantitative influence of the Martian crustal magnetic field on the global distribution of escaping pickup ions. In this paper, we apply a newly developed Monte Carlo ion transport model to address this problem. The background electromagnetic fields, in which test particles are followed, are calculated using an independent three-dimensional multispecies MHD model. The effects of the crustal magnetic field on particle escape are quantified by varying the crustal field orientation in the model setup and comparing the corresponding simulation results. The comparison is made by turning on or off the crustal field or changing the local time of the strongest field from the dayside to the dawnside. It is found that without the protection of the crustal magnetic field, the total amount of atmospheric escape through the tail region would be enhanced by more than a factor of two. It is shown that the crustal magnetic field not only regionally deflects the solar wind around the Martian atmosphere, but also has an important global effect on atmospheric erosion and thus on long-term atmospheric evolution.

1. Introduction

Without the shielding of a strong intrinsic magnetic field, the Martian atmosphere directly interacts with the impacting solar wind. The neutral constituents of the atmospheric corona can be ionized, and then picked up and accelerated by the magnetic field and convection electric field in the solar wind. This nonthermal escape process of heavy species is an important mechanism responsible for atmospheric erosion.

The interaction of Mars with the solar wind is mainly of the atmospheric type like Venus and comets. However, Mars is not a purely unmagnetized body but one with a crustal remanent field [1]. The existence of crustal magnetic anomalies and their local time change (with the strongest crustal field facing from the dayside to the nightside) due to the rotation of Mars are expected to be important factors to be taken into account in understanding the Mars-solar wind interaction and thus atmospheric erosion.

2. Numerical models

The major research tool in this study is a 3-D MHD field-based Monte Carlo ion transport model recently developed by Fang et al. [2]. The test particle model is designed to investigate pickup ion transport and acceleration in the context of the Mars-solar wind interaction. The finite heavy ion gyroradius effects are naturally included, which are due to the lack of a strong intrinsic magnetic field at Mars.

The transport of test particles is governed by the Lorentz force at the particle location determined from the magnetic field and convection electric field provided by the MHD model of Ma et al. [3]. The MHD model is a 3-D, non-ideal, multispecies, single-fluid model, solving for the bulk plasma parameters everywhere in the vicinity of Mars.

3. Results

In this paper, three cases are simulated and compared with each other. In case 1, the subsolar location of Mars is set to be at 180°W and 0°N; which places the strongest Martian crustal field on the dayside near noon. In case 2, the subsolar location is taken to be at 99.4°W and 25.3°N, with the strongest crustal field facing the dawnside. In case 3, crustal magnetic anomalies are not included in the MHD calculation. Mars in this case is a purely unmagnetized body with its dayside atmosphere and ionosphere withstanding the impacting solar wind.

Figure 1 shows the MHD simulation results for the bulk plasma velocity and electromagnetic fields in correspondence with the three crustal field configurations

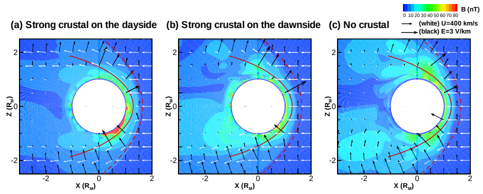

Figure 1: MHD simulation results for the magnetic field magnitude (color contour), vector field of the plasma velocity (white arrow), and convection electric field (black arrow) in the noon-midnight plane. The simulations are performed in three cases: (a) with the strongest Martian crustal magnetic field orientated toward the Sun, (b) with the strongest crustal field on the dawnside, and (c) with the crustal source neglected.

in the model setup. A close look at the results reveals that as the local time of the strongest crustal field changes from the dayside to the dawnside and then is removed (that is, from case 1 to case 2 to case 3), the subsolar BS(MPB) location moves inward toward the planet by around 7%(7%) and additional 3%(2%), respectively [3].

Figure 2 shows the escaping O^+ number flux distributions far down the tail (X=$-$4.0 Rm) when the orientation of the Martian crustal magnetic field is changed. It is clear that not only the spatial distributions of tailward moving particles but also the total escape rates depend on the location of the localized crustal magnetic anomalies. The finite heavy ion gyroradius effects manifest themselves differently within the different electromagnetic field configurations, which explains the prominent differences in the flux asymmetries for the different crustal orientations. Note that the crustal influence is seen as far as several Martian radii away from the surface.

The changes in atmospheric erosion as illustrated by Figure 2 are interpreted as reflecting the role of the Martian crustal magnetic field in the Mars-solar wind interaction. As the crustal field orientation changes from the dayside to the dawnside and is finally removed, the shielding force to the impacting solar wind is weakened, making the solar wind plasma penetrate deeper. A direct consequence is that the overlap region between the exosphere and the solar wind enters a denser atmosphere. More planetary particles are directly exposed to the solar wind, resulting in an increase of pickup ion production through the charge exchange and electron impact ionization collisions. More particles of planetary origin are therefore picked up and stripped away by the solar wind.

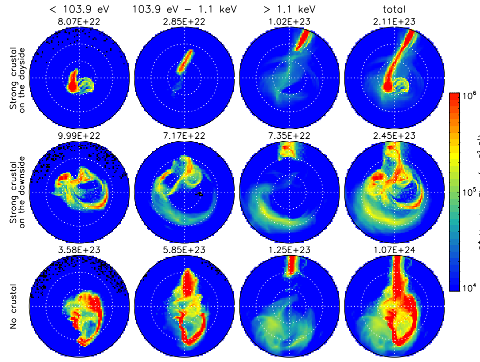

Figure 2: Comparison of escaping O^+ number flux distributions at X=$-$4.0 Rm when the configuration of the Martian crustal magnetic field changes in the three cases. The integrated flux intensities are marked on top of each panel in the unit of s^{-1}. The outer circles indicate a distance of 3 Rm from the X axis, and the dashed circles are spaced 1 Rm apart.

4. Conclusion

The comparison of the resulting tailward pickup ion flux distributions in the three cases shows that both the spatial distribution of escaping atmospheric particles and their integrated intensities in the Martian wake are affected by the crustal magnetic anomalies. While there is a slight increase in the total loss rate through the tail region from case 1 to case 2, the total erosion rate of the atmosphere is enhanced in case 3 by more than a factor of 2. More importantly, the spatial distribution of escaping number fluxes exhibits a dramatic change among the three cases. It is illustrated that the crustal magnetic field not only regionally deflects the solar wind around the Martian atmosphere, but also has an important global effect on atmospheric erosion. The impact of the crustal field on planetary particle escape to space implies that, in order to backward extrapolate the effects the ion pickup process has had on the ancient Martian atmosphere, the evolutionary remanent magnetic field is an important factor that needs to be included in the estimate of the atmospheric erosion rate.

Acknowledgements

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