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Ion escape fluxes from Mars

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[1] A 3D, multi-species, non-ideal MHD numerical code was used to calculate the ion escape fluxes from Mars. The calculations were carried out for six cases with different nominal solar wind, solar cycle and crustal field orientation conditions and the total escape fluxes (the sum of the three major ionospheric species, O^+, O_2^+, and CO_2^+) varied by about an order of magnitude from 2.7×10^{23} to 2.4×10^{24} sec^{-1}. These results were compared to the recently measured Mars Express results of 3.2×10^{23} sec^{-1} (O^+, O_2^+, and CO_2^+), which were obtained near solar cycle minimum conditions, indicating a good agreement between measured and calculated fluxes. We also calculated the escape flux for "extremely" high solar wind conditions which leads to a flux of 3×10^{25} sec^{-1}. **Citation:** Ma, Y.-J., and A. F. Nagy (2007), Ion escape fluxes from Mars, *Geophys. Res. Lett.*, *34*, L08201, doi:10.1029/2006GL029208.

1. Introduction

[2] In a recent paper *Barabash et al.* [2007] presented the results of their measured ion escape fluxes from Mars, which was measured by the ASPERA-3 (Analyzer of Space Plasma and Energetic Atoms) instrument [*Barabash et al.*, 2004] carried aboard the Mars Express spacecraft. These published values were nearly two orders of magnitude lower than earlier estimates based on data from observations obtained with instruments from the Phobos spacecraft [*Lundin et al.*, 1989; *Rosenbauer et al.*, 1989; *Verigin et al.*, 1991]. Therefore it is timely to again look at model calculations of these fluxes. In this paper we present results from new calculations obtained with our 3D, multispecies, non-ideal MHD model.

2. Modeling Details

[3] The paper by *Ma et al.* [2004] described our Mars model in quite some detail, so we will only summarize the main features and the changes we made since the publication. Our model is a 3D, non-ideal MHD model, which solves four continuity equations, a single momentum, a single energy and a magnetic transport/diffusion equations, using a spherical grid system. The four ions considered are O^+, O_2^+, CO_2^+ and H^+ and the fact that we only use single momentum and energy equations means that we assume single plasma velocities and temperatures. The ion chemistry used is reasonably complete, as detailed by *Ma et al.* [2004]. We use photoionization rates which take into account optical depth effects. The one important change we made recently is that instead of assuming a spherically symmetric neutral atmosphere, we use the results of the appropriate density and ionization rate from the 3D neutral atmosphere model of *Bougher et al.* [2000, 2006]. This model predicts significant variations of the density and temperature with solar zenith angle, as well as solar cycle; the model is constrained by observations from MGS (Mars Global Surveyor), Mars Odyssey and MRO (Mars Reconnaissance Orbiter). The hot atom densities were taken from *Kim et al.* [1998] and were assumed to be spherically symmetric. The calculations included both the H^+-O^+ charge exchange, as well as the photoionization and electron impact ionization effects; in order to calculate the latter we assumed that the electron temperature is half of the calculated plasma temperature and used the ionization rates given by *Cravens et al.* [1987].

[4] We used a computational domain, which is defined by $-24R_M < X < 8R_M$, $-16R_M < Y, Z < 16R_M$, where R_M is the radius of Mars (3396 km); the X axis points from Mars toward the Sun, the Z axis is perpendicular to the X axis and parallel to the projection of the planet rotation vector on a plane perpendicular to the X axis and the Y axis completes the right handed coordinate system. We selected such a large computational domain to insure that our results are independent of the outer boundaries. The nonuniform, spherical grid structure allowed a radial resolution that varied from 10 km at the lower boundary to 630 km near the outer boundary. The angular resolution varied from 1.875° to 3.75°.

[5] The lower boundary was set at 100 km and the O^+, O_2^+, CO_2^+ densities were taken to be the photochemical equilibrium values. The H^+ density was set to 0.3 cm^{-3}. A reflective boundary condition for **u** was used, which results in near zero velocity at the inner boundary as expected. The plasma temperature at the inner boundary was set to be twice the value of the neutral temperature, because at that low altitude, both ions and electrons have roughly the same temperature as neutrals. For solar minimum and maximum the neutral temperatures values were taken to be 117 and 134°K, respectively, and the pressures were set accordingly. The upstream solar wind plasma temperatures were set to 3.5×10^5 K, the interplanetary magnetic field (IMF) was assumed to be a Parker spiral in the X-Y plane with an angle of 56°. We carried out calculations for different interplanetary field magnitudes and solar wind density and velocity values, in order to evaluate their effects. We used the 60 harmonic expansions given by J. Arkani-Hamed (personal communication, 2001) to describe the observed [*Acuna et al.*, 1998] crustal magnetic fields. *Arkani-Hamed* [2004] showed that such an expansion is sufficient to represent the observed crustal fields.

[6] Our earlier calculations [*Ma et al.*, 2004] showed that our model agrees very well with the ionospheric results from Viking [*Hanson et al.*, 1977], as well as the bow shock

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Table 1. Input Parameters Used for the Different Calculations

	Solar Wind Density, cm^{-3}	Solar Wind Velocity, km/sec	Solar Condition	"Position" of Crustal Field
Case 1	2	300	solar minimum	0°
Case 2	2	300	solar minimum	90°
Case 3	2	300	solar minimum	180°
Case 4	4	400	solar minimum	0°
Case 5[a]	2	300	solar minimum	0°
Case 6	4	400	solar maximum	0°
Case 7[b]	20	1000	solar maximum	0°

[a]Case 5 is the same as case 1 except that charge exchange and impact ionization of the corona were not included.
[b]The magnetic field was set to B_y = 20 nT for case 7.

positions observations by Phobos and Mars Global Surveyor observations [*Vignes et al.*, 2000]. This gives us confidence to use our improved model to undertake a set of calculations to estimate escaping ion fluxes from Mars, resulting from ionospheric flows as well as charge exchange ionization processes.

3. Results

[7] We carried out calculations for seven different cases. We ran our model for solar minimum conditions (corresponding to an "Earth based" F10.7 of 70; that is the value of the 10.7 flux at the Earth) and assumed that the strongest crustal magnetic field position faced the Sun, was 90° and 180° away from the subsolar location. We ran these three cases (and will refer to them as cases 1, 2, and 3, respectively) in order to see how important an influence the crustal field orientation has on the escape flux. We assumed, for these three cases, a magnetic field magnitude of 3 nT and solar wind density and velocity of 2 cm^{-3} and 300 km sec^{-1}, respectively. We repeated our case 1 calculations for increased solar wind parameters of 4 cm^{-3} and 400 km sec^{-1}; we refer to that set of high pressure calculations as case 4. We turned off the photoionization and electron impact ionization terms for case 1, in order to get an idea of their importance; these calculations we refer to as case 5. We also carried out calculations for solar maximum conditions in order to see how large the variations in the escape flux are for changing solar conditions. These calculations again used neutral density and ionization rates from the Bougher model corresponding to an "Earth based" F10.7 of 200 the crustal magnetic field orientation was the same as for case 1. This set of calculations is referred to as case 6. In a very recent paper *Luhmann et al.* [2007] show, using Pioneer Venus observations, that during significantly increased solar wind pressure conditions the measured escaping ion fluxes from Venus was are very high. Prompted by these findings we ran a case (case 7) for solar maximum and extremely high solar wind parameters, to estimate how high the escape flux can be for such limited time periods. Table 1 summarizes the parameters used for the seven different cases and Table 2 presents the calculated fluxes.

4. Discussion

[8] We calculated by integrals of the plasma density times the radial velocity component at the surface of a sphere with appropriately far from the planet; we chose that to be at 5 R_m. We established that the calculated flux does not change to any significant degree as long as the radius exceeded about 4 R_M. Our model calculations indicate that while there are variations in the calculated escape fluxes during solar minimum, with the changing locations of the crustal magnetic field with respect to the subsolar position, these changes are within a factor of about two to three, which are probably within the range of uncertainties associated with the assumed parameters (e.g., neutral densities) in these calculations. The variations between solar cycle minimum and maximum conditions (cases 4 versus 6) is about a factor of 2.5, indicating that these fluxes do depend on solar cycle variations, but do not change by an order of magnitude or more and are significantly less than the values based on the Phobos observations. The drop of about nearly a factor of three in the O^+ escape flux, caused by the removal of photo and impact ionization is a clear indication of the important contribution of direct ionization of the extended oxygen corona. Solar wind pressure conditions during a "space weather event" are, as expected very high, and not surprisingly result in a significant increase in the escape flux. The increase is of an order of magnitude, but these conditions last only relatively short periods and thus their contribution to the overall escape rate is limited.

[9] These calculated numbers can now be compared with the fluxes obtained from the Mars Express ASPERA measurements (*Barabash et al.*, 2007), which correspond to solar minimum conditions and were obtained with variable crustal field locations. The measured values are 1.6×10^{23}, 1.5×10^{23} and 8×10^{22} sec^{-1} for O^+, O_2^+ and CO_2^+, respectively. The ASPERA instrument only measures ion fluxes with energies greater than about 30 eV, thus the fact that our estimated flux values are somewhat higher than the observed fluxes are expected and the measured and calculated values are reasonably consistent.

[10] Beyond comparing our results with the observed fluxes, it is appropriate to look at two recent model estimates of the escaping ion flux [*Modolo et al.*, 2005; *Harnett and Winglee*, 2006]. As indicated earlier the two main sources of the escaping ion flux are the dayside ionospheric plasma originating in a region between about 250 to 350 km on the dayside and charge exchange between the shocked solar wind and the neutral corona, as well as photo or electron impact ionization of this corona. The above mentioned two models, a hybrid and a multifluid MHD model, are excellent ones to address a number of important issues associated with the interaction of the solar wind with Mars, but not the ionospheric escape problem. The inner boundary of the multifluid MHD model [*Harnett*

Table 2. Calculated Escape Rate[a]

	O^+	O_2^+	CO_2^+	Total
Case 1	3.3×10^{23}	1.00×10^{23}	5.7×10^{22}	4.9×10^{23}
Case 2	4.7×10^{23}	2.8×10^{23}	1.1×10^{23}	8.6×10^{23}
Case 3	4.4×10^{23}	2.5×10^{23}	1.2×10^{23}	8.1×10^{23}
Case 4	7.2×10^{23}	1.9×10^{23}	1.3×10^{23}	1.0×10^{24}
Case 5	1.3×10^{23}	9.3×10^{22}	4.9×10^{22}	2.7×10^{23}
Case 6	1.8×10^{24}	4.1×10^{23}	1.8×10^{23}	2.4×10^{24}
Case 7	2.3×10^{25}	3.3×10^{24}	4.1×10^{24}	3.0×10^{25}

[a]Escape rates in sec^{-1}.

and Winglee, 2006] is at 300 km and the size of the first cell is 109 km, thus basically missing the ionosphere and therefore the calculated ionospheric outflow is set by the inner boundary conditions. Similarly the cell size of the hybrid model is 300 km; they establish their ionospheric plasma densities by the direct ionization of the neutrals and setting a value on the escape flux. Having said this, we can now proceed to compare our results with the ones from these two models. *Modolo et al.* [2005] estimate, for solar minimum conditions, escape fluxes of 5.2×10^{23} and 5×10^{22} sec^{-1}, for O^+ and O_2^+, respectively, with most of it coming from pick up ions and very little from the ionosphere, which may be the result of their large cell size in the ionosphere and their boundary conditions. The MHD results of *Harnett and Winglee* [2006] estimate an O_2^+ escape rate of 2.5×10^{25} sec^{-1} for their nominal case (solar wind density 2 cm^{-3}, u = 400km/s and B = 2nT); their calculated escape rate for all the other cases they considered is within the same order of magnitude. Their model only considered O_2^+ and thus they have no results for O^+.

[11] In summary our model predicts ion escape fluxes which are in good agreement with the latest observed values, indicating that our basic understanding of the current ion escape mechanism(s) from Mars are reasonably well in hand. Of course, there is still a great deal of uncertainty in predicting how these fluxes varied over the life of Mars and how they compare with other competing atmospheric escape processes.

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