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Role of plasma waves in Mars' atmospheric loss

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[1] Recent observations of plasma waves, electron fluxes, and ion fluxes in Mars' ionosphere indicate that ion heating may have had a significant impact on Mars' atmospheric loss. We discuss two energy sources of plasma waves: the solar wind interaction with Mars and field-aligned currents in regions of crustal magnetic fields. These plasma waves can damp through cyclotron resonance with the O^+ population in the ionosphere leading to heating and subsequent O^+ escape supporting the $\sim 10^{25}$ atoms s^{-1} ($\sim$0.4 kg/s) O^+ outflow indicated by present-day observations. A stronger solar wind and O^+ source of $\sim$4 Gyr ago could support losses of $\sim$100 kg/s, enough to strip Mars' atmosphere or 10 m of water in a $\sim$0.3 Gyr period. The observational evidence for ion heating is, with current data sets, largely circumstantial so we suggest needed observations. **Citation:** Ergun, R. E., L. Andersson, W. K. Peterson, D. Brain, G. T. Delory, D. L. Mitchell, R. P. Lin, and A. W. Yau (2006), Role of plasma waves in Mars' atmospheric loss, *Geophys. Res. Lett.*, *33*, L14103, doi:10.1029/2006GL025785.

1. Introduction

[2] The loss of Mars' atmosphere and oxygen derived from water has been the subject of intense debate for several decades [e.g., *Chassefiere and Leblanc*, 2004]. A number of hypotheses have been put forth encompassing surface chemical processes, photochemical processes, bombardment, and solar wind stripping. Many of these hypotheses are viable, but none have emerged as clearly dominant. We continue this debate with a discussion on how plasma waves leading to ion heating may have contributed Mars' atmospheric loss.

[3] Our analysis is motivated by recent reports of plasma wave intensities in Mars' ionosphere [*Espley et al.*, 2004], of energetic electron fluxes and field-aligned currents above crustal magnetic fields [*Brain et al.*, 2006], and of energetic ion fluxes emerging from Mars' ionosphere [*Lundin et al.*, 2004]. These reports provide solid evidence that ionospheric plasma processes, those acting from the exobase at $\sim$200 km in altitude to the ionopause at $\sim$1000 km in altitude, have sufficient energies to impact O^+ and O_2^+ outflow. O^+ and O_2^+ loss has been well studied [e.g., *Haider*, 1995; *Lammer et al.*, 2003] but the effects of plasma wave heating have not been considered fully. We show that plasma wave heating may cause a source-limited O^+ outflow in the present-day and could have support higher outflows with an enhanced O^+ source.

[4] Recent observations indicate two energy sources that can lead to ion heating. One energy source is the turbulence at the Martian bow shock, ionopause, and boundary layers that can propagate into the ionosphere as plasma waves. These waves first encounter the O^+ layer in the ionosphere which is essentially collisionless, and can energize these ions significantly. The observations of auroral-like phenomena at Mars [*Brain et al.*, 2006; *Bertaux et al.*, 2005] indicate a second energy source. The solar wind electric field on open field lines can drive currents in Mars' ionosphere leading to auroral-like phenomena such as electron beams and ion heating. We show that the latter energy source can greatly enhance ion outflows in local regions but is moderated by sparse coverage over the planet.

[5] The ion heating process is well documented at Earth [for review, see *André and Yau*, 1997]. Loss of heavy ions at Earth is dominated by a multi-stage, non-thermal process involving ionization in the lower ionosphere followed by plasma heating and acceleration at higher altitudes and, in turn, followed by loss down the tail. Ionization involves a number of photochemical processes including photo-ionization, electron impact ionization, dissociation, charge exchange, and collisional ionization. These source processes are balanced by recombination and loss. The resulting ions have a finite temperature/scale height and supply the upper ionosphere (above the exobase) through thermal diffusion. Plasma heating occurs at higher altitudes in a more tenuous, relatively collisionless plasma in which plasma waves and parallel electric fields deposit large amounts of energy per particle. The energization is such that the majority of ions that thermally diffuse to the heating altitudes are lost. This process also can be significant in a Mars-like environment.

2. O^+ Loss From Plasma Waves Generated by the Solar Wind Interaction

[6] We examine two solar wind energy mechanisms, (1) Poynting flux carried by plasma waves and (2) Poynting flux associated with field-aligned currents driven by the solar wind electric field. In this section, we discuss the former mechanism. Plasma waves can be generated by the solar wind causing turbulence at the bow shock [e.g., *Trotignon et al.*, 1996], turbulence at the ionopause [*Penz et al.*, 2005], and/or a Kelvin-Helmholtz instability at the flanks [*Penz et al.*, 2004]. Of the variety of plasma waves that are generated in the boundary layers, the shear Alfvén wave, the fast mode, and electromagnetic ion cyclotron waves are the most important for carrying energy over

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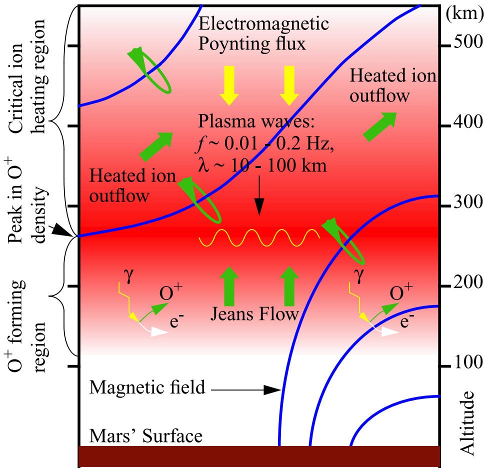

Figure 1. A cartoon of depicting ion outflow in Mars' ionosphere. The red shading represents the O+ density.

extended distances. At Earth, for example, shear Alfvén waves carry enough energy to power the aurora at the poleward boundaries where the strongest ion outflows are observed [*Wygant et al.*, 2000]. At Mars, we are not concerned with the exact generation mechanism of the waves but, instead, use observations of magnetic field fluctuations in the ionosphere to derive heating rates.

[7] Alfvénic wave power is confined to frequencies ≤ the H^+ cyclotron frequency of the generation regions. The magnetic field strength in the day-side boundary regions (~40 nT) is roughly a factor of ten higher than that in the solar wind ($B_{SW} \sim 3$ nT). As waves propagate into the Martian ionosphere ($B_I \sim 10$ to ~300 nT), they first encounter the O^+ ionospheric layer [*Hanson et al.*, 1977, *Penz et al.*, 2005] and become resonant with the O^+ gyrofrequency causing strong damping. It is important to recognize that, in Mars' ionosphere, the O^+ abundance peaks ($\sim 5 \times 10^8$ m^{-3}) at ~250 to ~300 km in altitude where the ionosphere is relatively collisionless. This layer also contains a large abundance of O_2^+ but, at least in some ionospheric models [e.g., *Penz et al.*, 2005], the O^+ densities dominate above ~300 km so we concentrate on O^+ heating. We show later that O^+ will absorb a large fraction of incident plasma waves. The densities of CO_2^+ and O_2^+ peak at lower altitudes, ~120 km, where neutral collisions cause strong wave damping so plasma processes are less effective. The O^+ layer is, in fact, ideally suited for plasma wave heating loss.

[8] Figure 1 depicts the basic ion heating process in Mars' ionosphere. The blue lines represent the induced magnetic fields, the exact local geometry is unimportant, and the red shade is the O^+ ionosphere. O^+ is created mostly below ~250 km in altitude by a number of processes [*Haider et al.*, 2002] resulting in a cold ($T_O \sim 0.1$ eV) O^+ source. At these altitudes the gravitational binding energy of O^+ (to infinity) is $\Phi_g = 2.1$ eV.

[9] We separate our discussion into two parts, the source flux and heating rates, either of which can restrict the ion outflow. The source flux of O^+ can be estimated as:

$$F_J = n_o v_{th} e^{-\Phi_g(z)/k_B T_o} \qquad (1)$$

where n_o is the peak plasma density, $v_{th} = (k_B T_O / 8\pi m_O)^{1/2}$ is the thermal velocity, k_B is Boltzmann's constant, m_O is the mass of O^+, and z is the altitude. The critical parameter for escape is the exponent, $-\Phi_g(z)/k_B T_O$, in Equation (1). Figure 2 plots the source flux as a function of altitude under four values of T_O. O^+ heating to ~1 eV can lead to $\sim 2 \times 10^{11}$ m^{-2}s^{-1} day-side outflow.

[10] Next, we examine how O^+ can gain energy to escape. Since there have been no measurements of electric fields (ΔE) in Mars' ionosphere in the low-frequency range, we use magnetic field observations which indicate spectral power densities of ~10–10^3 nT^{2}Hz^{-1} at ~0.04 Hz, the O^+ gyrofrequency with $\boldsymbol{B} \sim 40$ nT [*Espley et al.*, 2004, Figures 6 and 7 at lowest altitudes]. Estimating the ratio $\Delta E/\Delta B$ leads to a large uncertainty. One assumption is that $\Delta E/\Delta B = v_A$, where v_A, the Alfvén velocity, is $\sim 2 \times 10^{-4} c$ just above the O^+ layer (~400 km in altitude). The electric field spectral power density is likely to lie between $\sim 4 \times 10^{-8}$ V^{2}m^{-2}Hz^{-1} and $\sim 4 \times 10^{-6}$ V^{2}m^{-2}Hz^{-1}. A more optimistic assumption is that $\Delta E/\Delta B \sim 10 v_A$ since Alfvénic waves become more electrostatic near the ion cyclotron frequencies and through the process of phase mixing [*Chaston et al.*, 2004]. We estimate an upper bound of 4×10^{-4} V^{2}m^{-2}Hz^{-1}. Such amplitudes are not unusual at Earth.

[11] The O^+ heating rates can be estimated from cyclotron resonant heating [*Chang et al.*, 1986]:

$$W = \frac{e^2}{2m_o} \eta_L S(f_{O+}) \qquad (2)$$

where e is the fundamental charge, η_L is the fraction of wave power that is left-hand polarized, and $S(f_{O+})$ is the electric field power density at the O^+ cyclotron frequency (f_{O+}).

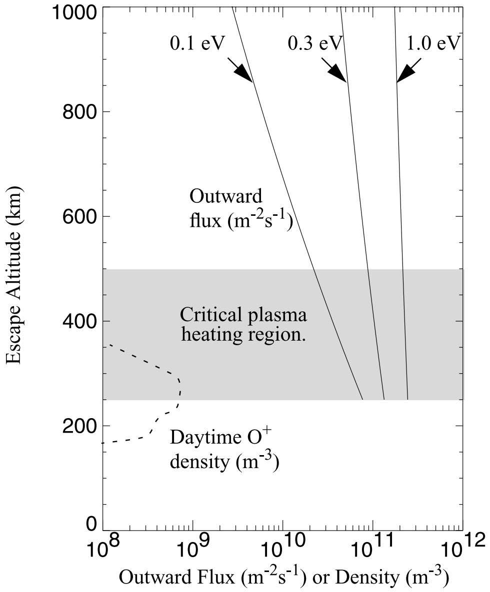

Figure 2. O^+ outflow of ions is a strong function of the escape altitude and the ion and electron temperatures. Plasma wave activity between ~250 km and ~500 km can lead to O^+ outflows up to $\sim 2 \times 10^{11}$ m^{-2}s^{-1}. The solid lines are the thermal outflow as a function of the heating altitude assuming that $T_e + T_O = 0.1$eV, 0.3 eV, and 1.0 eV, where T_e is the electron temperature and T_O is the O^+ temperature The dashed lines are a model density profile derived from *Penz et al.* [2005].

The observations indicate significant heating rates from $\sim 5 \times 10^{-2}$ eV s^{-1} to ~ 500 eV s^{-1} assuming $\eta_L = 50\%$.

[12] The Poynting flux $\Delta \boldsymbol{E} \times \Delta \boldsymbol{B}/\mu_o$ near f_{O+} ($\cong 0.04$ Hz with $\boldsymbol{B} = 40$ nT) in the ionosphere ranges from $\sim 5 \times 10^{-9}$ W m^{-2} to $\sim 5 \times 10^{-6}$ W m^{-2} using a 0.01 Hz band width. Since f_{O+} changes as the waves penetrate into the ionosphere, O^+ can resonate with a broad band of waves. This calculation makes the assumption that the Poynting flux is directed toward the ionosphere which is almost always the case at Earth [*Wygant et al.*, 2000]. For comparison, we consider the energy flux ($\sim 3 \times 10^{-8}$ W m^{-2}) needed to support O^+ outflow of 2×10^{11} $m^{-2}s^{-1}$ assuming the average energy gain by O^+ is ~ 1 eV (see Figure 2). An outflow of 2×10^{11} $m^{-2}s^{-1}$ from 1/2 of Mars' ionosphere will result in an planetary loss of 10^{25} s^{-1}, the value estimated by observations [*Lundin et al.*, 1989; *Verigin et al.*, 1991]. The pessimistic assumptions yield a Poynting flux that is short by an order of magnitude; the optimistic assumptions indicate that plasma waves have over two orders of magnitude more energy than needed and can result in higher energy O^+ (10's of eV). We point out that the gyroradius of O^+ trapped on close field lines will increase to >25 km ($T_O = 1$ eV, $B = 40$ nT) and, therefore, with somewhat higher heating (~ 10 eV), can escape as well.

[13] A key element of our hypothesis is that O^+ heating efficiencies are high. A Poynting flux of $\sim 5 \times 10^{-8}$ W m^{-2} implies a heating rate of 5×10^{-2} eV s^{-1}. The peak O^+ density of $\sim 5 \times 10^8$ m^{-3} leads an absorption per unit distance of $\sim 4 \times 10^{-12}$ W m^{-3}. The wave power will e-fold in $\sim 10^4$ m or 10 km (the e-fold distance is independent of the incident power). The O^+ layer is several times thicker, so one can expect nearly 100% absorption of the left-hand polarization near f_{O+}.

[14] O_2^+ heating also needs to be considered. The spectral power density at f_{O2+} is flat and nearly the same as f_{O+}, but O_2^+ will resonate with a smaller frequency band. The heating rate (Equation 1) also is inversely proportional to mass and O_2^+ requires twice the energy to escape. Moreover, as waves propagate from lower to higher magnetic field strengths, they resonate with f_{O+} before resonating with f_{O2+} and O^+ can deplete the power, so we expect lower O_2^+ outflows, as reported by *Lundin et al.* [2004]. As a cautionary note, the referenced ion observations at Mars are restricted to energies greater than 10 eV and may represent the tail of the heated ion distributions.

[15] A discussion of the magnetic field geometry and mixing of O^+ with the solar wind plasma is beyond the scope of this paper. A hybrid simulation [*Kallio and Janhunen*, 2002] that assumes a large O^+ supply (10 eV) from the ionosphere indicates that the O^+ ultimately retreats down the tail region. For completeness, we mention that the our mechanism can complement energization from solar wind electric field penetration into Mar's ionosphere. Measurements of the low-energy ion flow and the electric field wave power in Mars' ionosphere are needed to test both hypotheses.

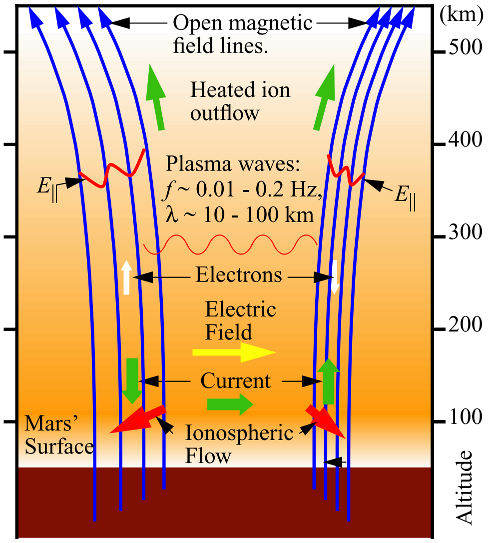

Figure 3. A cartoon of the "auroral region" at Mars. The orange shading represents the electron density. Currents are driven from the solar wind electric fields penetrating to Mars' ionosphere. Auroral currents often result in electron acceleration and plasma waves which heat ions.

3. O^+ Loss From Plasma Waves Generated by Electron Beams and Field-Aligned Currents

[16] Another energy source, the Poynting flux associated with field-aligned currents driven by the solar wind electric field (E_{SW}), may be important in regions of strong crustal magnetic fields. The basic idea is that E_{SW} penetrates open-field lines driving currents and flows in Mars' ionosphere (Figure 3). The majority of the energy is dissipated via Joule heating in the dense CO_2^+ and O_2^+ ions in the lower ionosphere. However, two types of auroral effects can cause strong ion heating in the O^+ layer (~ 250 to ~ 500 km). As in the case on Earth and the outer planets, a fraction of the Poynting flux can be converted into electron energy flux and ion energy flux via acceleration by parallel electric fields in the regions where the field-aligned currents are strongest. Observations of electron fluxes associated with crustal magnetic fields [*Brain et al.*, 2006] indicate currents of ~ 0.5 $\mu A/m^2$ carried by ~ 200 eV electrons and electron energy fluxes of $\sim 10^{-5}$ W/m^2. A second effect which may be particularly important in Mars' O^+ ionosphere is the generation of ion cyclotron waves from a current-driven instability [*Kindel and Kennel*, 1971; *Cattell*, 1981].

[17] Using an analogy to Earth's aurora, the accelerated electrons can generate intense plasma waves which transfer $\sim 1\% - \sim 5\%$ percent of the electron energy flux to ions. More importantly, the currents directly generate ion cyclotron waves with energy fluxes up to a significant fraction of the electron energy fluxes. From this analogy, we can expect up to a few times 10^{-6} W m^{-2} of energy into ion heating in the O^+ layer on Mars in regions of field-aligned currents. This energy deposition, however, is confined to a very small area of the Martian ionosphere.

[18] The downward electron energy fluxes have another important consequence, they can enhance the O^+ source. Ultimately, electrons deposit all of their energy in the ionosphere increasing the ion density and creating a secondary electron population. The ambipolar electric field created by the warm electrons will raise the scale height of O^+ causing a large flow into the ion heating regions. In the auroral regions at Earth, cusp ion fluxes are routinely observed between $10^{12} - 10^{14}$ $m^{-2}s^{-1}$.

[19] A detailed photochemical analysis is required to understand the full effects of electron impact ionization, so we make only a rough estimate of the present-day O^+ loss in Mars' crustal magnetic field regions based on an analogy to Earth's cusp regions. Earth's high rate of 10^{14} $m^{-2}s^{-1}$ leads to an upper bound. Electron beams are seen in roughly ~0.5% of the measured electron distributions [*Brain et al.*, 2006], so the global O^+ loss could be as high as $\sim 5 \times 10^{25}$ s^{-1}. This value, while speculative, is ~5 times that observed. Ion outflow at crustal magnetic fields is worthy of investigation.

4. Discussion and Conclusions

[20] We have analyzed plasma wave heating and O^+ loss at Mars using the best available plasma observations in Mars' ionosphere. We have shown that it is possible that plasma wave heating in the upper ionosphere can bring $\sim 10^{25}$ atoms s^{-1} O^+ to the ionopause on the day side and flanks of Mars. As shown by simulation [*Kallio and Janhunen*, 2002], the O^+ ultimately retreats down the magnetotail and is consistent with the observed cold ion flow in Mars' magnetotail [*Lundin et al.*, 1990]. Two viable energy sources for ionospheric plasma waves are plasma waves propagating in from boundary regions and auroral processes, that is, electron beams and current-driven instabilities, seen in regions of crustal anomalies.

[21] Less than 0.1% of the incident power carried by the solar wind ($\sim 10^4$ W m^{-2}) is needed for $\sim 10^{25}$ atoms s^{-1} O^+ to escape Mars' gravity, but ~10 times the incident solar wind power is needed to accelerate the escaped O^+ to solar wind speed. Thus the bulk of the energization will occur in Mar's magnetotail drawing solar wind kinetic energy from a larger region.

[22] An enhanced O^+ ionosphere (higher density) would be needed for plasma wave heating to contribute significantly to Mars' atmospheric loss in the past. Previous analyses [*Lammer et al.*, 2003, and references therein] have noted that O/O^+ escape rates are not consistent with H escape. Under our hypothesis, O^+ loss can be restricted either by the source rate or by the energy input. We argue that the present-day O^+ escape is likely to be source limited; the wave Poynting flux is adequate unless we use the most pessimistic numbers. The past ionosphere, however, could have been far richer in O^+ (more Earth-like), so the energy input may have been the key factor. The upper bound of the present-day plasma wave energy input into the ionosphere ($\sim 5 \times 10^{-6}$ W m^{-2}) could support 100 kg/s mass loss, enough to strip Mars' atmosphere or 10 m of water in 0.3 Gyr. Furthermore, several conditions in the past may have increased energy input: (1) a more active solar wind, (2) more turbulent boundary layers from higher density ionosphere, and/or (3) more abundant or intense electron beams and current-driven heating. It is possible, then, that ion heating by plasma waves may have had an impact on Mars' atmospheric loss.

[23] The role of plasma wave heating is uncertain with the current data set. However, the combination of (1) observations that plasma waves do penetrate to the ionosphere [*Espley et al.*, 2004], (2) that these waves will first encounter the collisionless O^+ layer and are in the proper frequency range to heat O^+ (because of Mars' weak magnetic field), and (3) that ion outflows have been observed [*Lundin et al.*, 2004] provide favorable circumstantial evidence. Measurement of low-energy (~1 eV) ion outflow and electric field wave power, in addition to magnetic fields and electrons, would remove many uncertainties on the present-day ion heating process in Mars' ionosphere which, in turn, will allow us to define the role of plasma waves and ion heating in the past.

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