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Cold ion escape from the Martian ionosphere

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ABSTRACT

We here report on new measurements of the escape flux of oxygen ions from Mars by combining the observations of the ASPERA-3 and MARSIS experiments on board the European Mars Express spacecraft. We show that in previous estimates of the total heavy ion escape flow the contribution of the cold ionospheric outflow with energies below 10 eV has been underestimated. Both case studies and the derived flow pattern indicate that the cold plasma observed by MARSIS and the superthermal plasma observed by ASPERA-3 move with the same bulk speed in most regions of the Martian tail. We determine maps of the tailside heavy ion flux distribution derived from mean ion velocity distributions sampled over 7 years. If we assume that the superthermal bulk speed derived from these long time averages of the ion distribution function represent the total plasma bulk speed we derive the total tailside plasma flux. Assuming cylindrical symmetry we determine the mean total escape rate for the years 2007–2014 at $2.8 \pm 0.4 \times 10^{25}$ atoms/s which is in good agreement with model estimates. A possible mechanism to generate this flux can be the ionospheric pressure gradient between dayside and nightside.

1. Introduction

The escape of ions from the atmospheres of the terrestrial planets and its importance for planetary evolution have been discussed vividly by many authors in recent years since more and more data are being collected and models are being refined. For the case of Mars the importance of ion escape for the evolution of the Martian water inventory has been recently reviewed by Lammer et al. (2013). These authors conclude that Mars lost the major part of its primordial wet atmosphere during the first 500 million years since solar system formation, the remaining thin atmosphere has since then been suffering from a continuous loss of hydrogen and oxygen atoms into space by different processes. Observations of the hydrogen day glow of Martian exosphere show that the Jeans escape of hydrogen is on the order of 1.5×10^{26} atoms/s. The origin of the escaping hydrogen must be water molecules evaporating from the Martian soil. This means that with any two hydrogen atoms escaping into space one oxygen atom is left in the atmosphere. But since oxygen content of the atmosphere is negligible and oxidation of the soil seems to be small, the escape of oxygen atoms from Mars into space should be about 0.75×10^{26} ions/s (Lammer et al., 2003).

Current models indicate that the loss of neutral oxygen by the energization of a hot oxygen corona may be the dominant oxygen loss process with loss rate estimates varying between 0.6 and 21×10^{25} atoms/s depending on model and solar activity (Fox and Hać, 2009). A more recent estimate by Gröller et al. (2014) puts it at $2.3–2.9 \times 10^{25}$ atoms/s. Unfortunately up to today it was not possible to measure the neutral hot oxygen flux directly leaving ample space for speculation. Technically it is much easier to measure escaping oxygen ions which originate either from the ionization of the neutral corona or directly from ionospheric outflow.

The ion loss rate was measured for the first time by instruments on the Phobos spacecraft – reporting values between 5×10^{24} ions/s (Verigin et al., 1991) and 3×10^{25} ions/s (Lundin et al., 1989). But these observations were very limited by the small number of orbits achieved by the Phobos mission and other instrumental constraints. Since February 2004 the Mars Express (MEX) spacecraft is in orbit around Mars with the ASPERA-3 instrument being dedicated to measure the ion flux at spacecraft position (Barabash et al., 2006). Using these data a large number of studies have been published trying to determine the average value and variability of the escape rate of heavy ions from Mars

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(Carlsson et al., 2006; Barabash et al., 2007; Lundin et al., 2008a,b; 2009; 2011a,b; Edberg et al., 2010; Frahm et al., 2010; Nilsson et al., 2010, 2011) – reviewed by Dubinin et al. (2011) and Lundin (2011). Current estimates for the total ion loss rate from these studies vary between 0.01 and 0.8×10^{25} ions/s depending on solar activity during observation and analysis method applied – a rate smaller but still comparable to the neutral atom loss rate.

But all of these studies suffer from the facts that (1) the field of view of the ion spectrometer IMA of the ASPERA-3 experiment – especially for ions below 50 eV/q is only $6° \times 360°$, (2) the low-energy cut-off of the instrument is at 10 eV/q, and (3) ions are pre-accelerated by a varying spacecraft potential which often is poorly constrained. We have shown in a previous study (Fränz et al., 2010) that this means that an absolute determination of the low-energy ion flux from ion spectrometer data alone is impossible. This problem is not unique to the ASPERA-3 instrumentation but it has been reported recently that cold ions may play a major role in solar system plasmas but are difficult to detect (Engwall et al., 2009; André and Cully, 2012). Fortunately the Mars Express carries as well the radar instrument MARSIS which can determine local electron density and magnetic field intensity as well as top-side ionospheric electron density profiles (Gurnett et al., 2005; Jordan et al., 2009). In Fränz et al. (2010) we have combined the MARSIS plasma density measurements with the ASPERA-3 observations to achieve a determination of the cross-terminator heavy ion flux in the altitude range of 290–400 km. This determination was possible at that time only on 7 orbits in 2007 with good observation geometry. We could show that the high ratio between the plasma densities observed by MARSIS and ASPERA-3 can be explained by the inclination angle between the IMA field of view plane and a strictly tailward flow direction.

The magnetic clock-angle coverage on these orbits was between 20° and 60° – assuming cylindrical symmetry around the Mars–Sun axis results in a total heavy ion flux of between 2 and 5×10^{25} ions/s across the terminator in this altitude range. Assuming that the flux estimate was statistically representative and citing model calculations by Ma et al. (2004) we speculated that about half of this cold ion flux may escape leading to a significantly higher escape rate estimate compared to previous studies based on ASPERA-3 data alone. The reason for the significant difference was that the ASPERA-3 ion spectrometer is only rarely capable of determining the cold ion density even if temperature and mean velocity of the cold ions can be determined.

Since 2007 the MARSIS and ASPERA-3 instruments have collected many more data especially on the nightside of Mars. The combination of both data sets allows us now to study the evolution of the cold ion flux from the terminator tailward up to the maximum distances with MARSIS coverage (at about 1600 km altitude) to investigate what part of the cross-terminator cold ionospheric flow eventually escapes from the planet. In this paper we describe all constraints of the respective data sets and make estimates on the possible rates of cold ion escape from Mars.

2. Instruments

2.1. The ASPERA-3 plasma spectrometers

The MEX spacecraft is in a highly eccentric polar orbit around Mars with periapsis and apoapsis of ~275 and 10 000 km, respectively. The ASPERA-3 (Analyzer of Space Plasma and Energetic Atoms) experiment is a combination of in situ and remote diagnostics of atmospheric escape induced by the solar wind. It comprises the Ion Mass Analyzer (IMA), ELectron Spectrometer (ELS), Neutral Particle Imager (NPI) and Neutral Particle Detector (NPD) (Barabash et al., 2006). The Ion Mass Analyzer (IMA) determines the composition, energy and angular distribution of ions in the energy range 10 eV/q – 25 keV/q . Mass (m/q) resolution is provided by combination of the electrostatic analyzer with deflection of ions in a cylindrical magnetic field set up by permanent magnets. Patches uploaded in May 2007 and December 2009 have further improved the IMA performance, extending the energy range down to cold/low-energy ions (≤ 10 eV). In the energy range ≥ 50 eV, it measures fluxes of different (m/q) ion species with a time resolution of 192 s and a field of view of $90° \times 360°$ (electrostatic sweeping provides elevation coverage $\pm 45°$). The measurements of the cold/low-energy component (≤ 50 eV) are carried out without this elevation sweeping but with an increased time-resolution of these 2D-measurements of 12 s. The field of view for low-energy ions is $6° \times 360°$ with an azimuthal angular resolution of 22.5°. The effective energy resolution of the ion sensor is $\delta E/E = 9\%$, the nominal mass resolution of about $M/\delta M = 6.0$ is in principal sufficient to discriminate between O^+ and O_2^+ ions, but drops to $M/\delta M = 3.5$ at energies larger than 100 eV. In this paper we use ASPERA-3 IMA spectral data only which have been cleaned of background noise and separated into light and heavy ions by software developed by Fedorov (the so-called IMAEXTRA data). The ELS sensor measures 2D distributions of the electron fluxes in the energy range 1 eV–20 keV ($\delta E/E = 8\%$) with a field of view of $4° \times 360°$ and a time resolution of ~4 s. A grid usually biased at -5 V protects the sensor from low energy photo-electrons but also inhibits measurement of the cold electron component (≤ 5 eV) of the plasma.

2.2. The MARSIS local plasma density determination

The MARSIS (Mars Advanced Radar for Subsurface and Ionospheric Sounding) radar sounder ($f \approx 0.1$–5.5 MHz) on Mars Express is designed to monitor the topside ionospheric height profile and the subsurface of the planet (Nielsen, 2004; Jordan et al., 2009). It consists of a 40 m tip-to-tip electric dipole antenna, a radio transmitter, a receiver, and a digital signal processing system. For the normal ionospheric sounding mode used by MARSIS the transmitter steps through 160 frequencies ($\Delta f/f \approx 2\%$) from 100 kHz to 5.5 MHz. The receiver has a bandwidth of 10.9 kHz centered on the frequency of the transmitted pulse. A complete scan through all 160 frequencies takes 1.26 s, and the basic sweep cycle is repeated once every 7.54 s. The measurements were made only at altitudes ≤ 1600 km. In addition to remote radio sounding, the local electron density and the magnetic field strength can also be obtained from MARSIS by measuring the frequencies of local electron plasma oscillations ($f_{pe} = \sqrt{n_e e^2/\pi m_e}$) and electron cyclotron waves ($f_{ce} = eB/2\pi m_e c$) and its harmonics excited by the radar transmitter in the nearby plasma (Gurnett et al., 2005, 2008; Duru et al., 2008). If the plasma frequency is below the lower limit of the frequency of the receiver (100 kHz) which often happens at high altitudes, the electron plasma frequency cannot be observed. However, its harmonics generated by distortion in the pre-amplifier due to very large amplitudes of the waves still allow a determination of electron densities as low as 20 cm^{-3} by measuring the spacing of the harmonics. The accuracy for measuring the electron density is about of $\pm 2\%$ (Duru et al., 2008). Some other factors (the harmonic spacing must be ≥ 30 kHz, plasma speed ≤ 160 km/s, the electron temperature $\leq \sim 0.73 n_e$ (cm^{-3}) eV) impose additional constraints on the density measurements ($n_e \geq 10$–20 cm^{-3}) (Duru et al., 2008). The electron cyclotron echoes which usually are present in the magnetic fields greater than few tens of nT, are excited by the cyclotron motion of the electrons accelerated by the radar wave pulses (Gurnett et al., 2005; Akalin et al., 2010). Unfortunately the Mars Express spacecraft does not carry a magnetometer and a Langmuir probe which would allow a direct measurement of these parameters. The identification of the harmonics in the MARSIS ionospheric spectra