Cold Ion Escape from the Martian Ionosphere

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Plasma Instruments on Mars Express

Mars Express Radar Electron density B total

Orbit Insertion 28 Jan 2004

Mars Express Orbit 20040201_20040209

PERICENTER ~260 km
7.5h orbit
APOCENTER 4.5Rₘ

Ion Spectrometer IMA, 3D, 16x16 sectors 10eV–40keV, 32 mass rings
MEX: Below 50eV electrostatic scanner is switched off: only 2D measurement!
Acceleration of ions across the terminator at Venus can be explained by the day-night pressure gradient in an inviscid collisional plasma (Elphic et al., GRL, 1984).
MARS
Previous ion escape determinations based on ASPERA3 alone

Figure 3. Low-energy (<200 eV) planetary heavy ion (O$^+$, O$_2^+$, CO$_2^+$) fluxes near Mars. Colour scale represents average fluxes in the 500×500 km quadrants.

Escape rate 0.15-0.45 RM downstream of terminator:
2.0-3.7 $10^{24}$ ions/s
(Lundin et al. GRL 2008a, Nilsson et al. 2011)

1 order lower than expected from models (Fox et al. 2008)
and Phobos observations.

Dependence of escape on solar wind pressure
(Lundin et al. GRL 2008b)
We observe O+ densities of 2000±200/cm³ and a bulk speed of 6±1km/s corresponding to a flux of 0.9 $10^9$/cm²s over the altitude range 290-400km.

If we assume that this flux is constant over a 100km shell around the terminator we get a lower limit for the ionospheric escape flux of 2.5±0.5 $10^{25}$ions/s.

This agrees well with models of the ionospheric dayside upward ion flow (Fox, 2009) but is 10 times higher than the value reported for the heavy ion flow downstream of the terminator (Lundin et al. 2008, Nilsson et al. 2011).

Does the transterminator flow of about 3x$10^{25}$ions/s escape?
New MARSIS nightside observations in 2007-2014

Combined observations of MARSIS, ASPERA-ELS and ASPERA IMA. Many orbits with nightside plasma density >100/cc but very low IMA density.
New MARSIS nightside observations in 2007-2014

On some orbits MARSIS and IMA agree when IMA field of view and SC potential fit.

- High plasma density
- High IMA signal
- Hot ions
- Cold ions
- Dayside
- Nightside
- Shadow

Density [cm$^{-3}$]
Ions [eV]
Flux [cm$^2$/s]
Electrons [eV]
Angle [deg]
Pos R_M [R$_{Mars}$]
MEXDist [hmm UT 0300]
2009 Apr 08
IMA plane
90°
Zenith angle
2.0
R$_{Cyl}$
Distance
At energies < 50eV ASPERA IMA measures only a in a 2D plane with 4deg polar width. Idea to overcome this: sample a mean velocity distribution (VD) from many orbits.

Problem: the missing observations at E<10eV can not be reconstructed from the mean VD.
Total flux of heavy ions from MEX Aspera IMA observed between 1 May 2007 and 1 March 2011.
Top: from Nilsson et al. (2012), scaled in \( \text{c/m}^2\text{s} \)
Bottom from Imaextra Heavy averaged VD adding low (<50eV) and high (>50eV) energy, scaled in \( \text{c/cm}^2\text{s} \).
Mean VD function of ions (<50eV) from MEX Aspera IMAEXTRA VD observed between May 2007 and March 2011, n s^{-3}/km^{6} vs km/s. Top without SC velocity and SC potential correction, bottom with SC velocity and SC potential correction.

Integrated density from mean VD function of ions (<50eV) from MEX Aspera IMAEXTRA observed between 2007 and 2011, in c/cm^{3}. Top without SC velocity and SC potential correction, bottom with SC velocity and SC potential correction.
Comparing ASPERA and MARSIS densities (ions/cc)

Integrated density of heavy ions (<50eV) from MEX Aspera IMAEXTRA VD observed between 2007 and 2011, scaled in /cm3s with SC velocity and SC potential correction.

Aspera

Marsis

Mean total electron density observed by MARSIS plasma frequency. Observations 2007-2014 allow higher spatial resolution.

Mean total electron density observed by MARSIS plasma frequency observations (same scale and time range).
Median cold heavy ion flux
from all orbits in between 05/2007 and 07/2014
where both IMA and MARSIS data are available

Mean heavy ion tailward velocity (km/s, top) and total flux (/cm²s, bottom) by multiplication of MARSIS density and IMA VD Velocity (corrected for spacecraft velocity and potential).
Median cold heavy ion flux
from all orbits in between 05/2007 and 07/2014
where both IMA and MARSIS data are available

Tailward flux becomes constant beyond 0.5 R_M tailward distance
and main flux is between 0.9 and 1.3 R_M cylindrical distance
from tail axis resulting in a median escape rate of $2.8 \times 10^{25}/s$.

Median heavy ion flux ($/cm^2 s$) by multiplication of MARSIS density and
IMA Velocity (corrected for spacecraft velocity and potential).
Here the minimum of a set of different velocity measures is taken.

Total cold ion flux (IMA velocity X MARSIS density) as function
of tailward distance from terminator for different cylindrical rings around tailaxis.
Mean escape of oxygen ions at solar minimum are 10 times higher than in previous studies by Lundin et al. 2008 and Nilsson et al. 2011 for following reasons:

1. Shift of energy table by varying spacecraft potential was not taken into account
2. the extrapolation from a 2D measurement to 3D distribution function neglected angular offset from bulk flow direction.
3. distribution function was assumed to be static in time (Nilsson et al. 2011)
4. Obscuration by spacecraft was not taken into account properly.
5. No absolute reference for plasma density was used.

Significant sources of error in this study:

1. Spatial coverage of MARSIS observations is limited to 1600km altitude
2. Plasma density can only be measured when >10/cc
3. Plasma density determination methods disagree below 100/cc
4. Spacecraft potential often ill defined by ELS observations.
5. Mean velocity often ill defined when IMA obscured by spacecraft.

Combination of Aspera-3 and MARSIS:

• Allows for the first time to explain the partial plasma density observed by particle sensors by an angular offset of a Maxwellian plasma distribution
• It confirms that in the terminator region the upper ionosphere is moving at super-sonic speed causing an oxygen ion passage of >2 \(10^{25}\) ions/s across the terminator
• We can now confirm using 2007-2014 data that the larger part of this cold ion flow escapes. This means total mean escape flux is 10x higher than previously reported by MEX Aspera because effect of 2D measurement has not been considered in previous studies.
• Acceleration of ions can be explained by transterminator pressure gradient as for Venus but the speed exceeds escape velocity only at Mars.
• Energetic flux observed in central plasma tail has much lower density and does only contribute less than 10% of total ion outflow.