Supporting Online Material for
Martian Atmospheric Erosion Rates
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DOI: 10.1126/science.1134358

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Materials and Methods
The IMA is a top-hat electrostatic analyzer followed by a circular magnetic velocity separating section. A large diameter MCP with a discrete anode images the matrix azimuth \(\times\) mass. The IMA provides ion measurements in the energy range 0.03 - 30 keV/charge with the energy resolution 5% within the instantaneous field of view 4.6° \(\times\) 360°. Electrostatic sweeping performs elevation (±41°) coverage. In its maximum resolution mode, the IMA provides 96 energy steps, 16 azimuth sectors, 16 elevation angles, and 32 mass rings. The total IMA field of view is 90° \(\times\) \(\sim\) 1.8 sr is partially blocked by the spacecraft body (ca 15%). The energy sweep for energies below 300 eV is organized in such a way that the energy difference between two adjacent steps was 15 – 50% of the central step energy. Because of the 5% energy resolution of the electrostatic analyzer, it resulted in some “gaps” in the distribution function measurements. It was, however, taken into account by proper interpolation between steps and did not contribute to the measurement error because of the ion distribution function is sufficiently wide in this energy range. Despite that the instrument is capable of detecting ions down to the 10 eV energy level, the measurements below 30 eV were regarded not sufficiently reliable (mostly due to unknown spacecraft potential) and the lower energy limit was set at 30 eV. The sampling time is 125 ms per energy level. In the full resolution mode, the IMA measures the distribution function over the full energy- and elevation range during 96 \(\times\) 16 \(\times\) 0.125s = 192 s. With the spacecraft velocity of 2 – 5 km/s, this corresponds to a spatial resolution along an orbit of 380 – 960 m = 0.11 - 0.28 R_m where R_m is the Martian radius (Fig S1).

Uncertainties in escape rate measurements
1. **Not full coverage over solid angle.** The flux directions are close to the solar wind direction (see section Morphology of the interaction region). Since the IMA field of view “equatorial plane” coincided almost all the time with the ecliptic plane, the solid angle coverage was sufficient for the study. Also, the electrostatic sweeping is less reliable for ions of an energy less than 100 eV, resulting in less coverage for the low energy ion measurements.

2. **No mass separation between O\(_2^+\) and CO\(^+\).** The CO\(^+\) density at the 300 km height is around 100 times lower than that of O\(_2^+\) (6). Therefore, \(Q(\text{CO}^+) / Q(\text{O}^+) \approx 0.01 \cdot Q(\text{O}_2^+) / Q(\text{O}^+) = 9 \cdot 10^{-3}\) and \(Q(\text{CO}^+) / Q(\text{CO}_2^+) = 2\%\). We can therefore neglect the contribution of the CO\(^+\) ion in the overall escape of oxygen and carbon in the escape channel under consideration.

3. **Not full mass separation between O\(_2^+\) and CO\(_2^+\).** Because of fully automatic procedures for the mass fitting used in this study, the mass separation between O\(_2^+\) and CO\(_2^+\) may contribute by a factor of 2 in the difference in the ratio between these two components, although the total escape rate \(Q(O^+) + Q(O_2^+) + Q(CO_2^+)\) is not affected.

4. **Deviation of the flux direction from the \(-X\) axis.** The deviation of the flux direction from the solar wind direction is well within 45°. Therefore, the maximum error factor cannot exceed \(cos(45°)/2 = 0.35\), i.e., the uncertainty factor is within \(-35\%\)…\(+0\%\).

5. **Uncertainties in the geometrical factor for low energies (< 300 eV).** The calibrations of the instrument at low energy ranges, below ca 300 eV, are challenging and cannot
provide reliable values of the geometrical factor. Ray tracing of the instrument mathematical model, which in turn was verified against the flight model laboratory calibrations, was used to obtain the geometrical factor values used in this study. To estimate the possible errors in the total flux estimations due to uncertainties in the geometrical factor value below 300 eV, we first constructed energy spectra of the planetary ion flux (O$^+$ + O$_2^+$ + CO$_2^+$), averaged over the observation time and space separately in the magnetic pileup region (MPR) and in the plasma sheet (PS) (see Figure 2, main text). The peak of the PS distribution in the 300 eV – 2 keV energy interval demonstrates the main property of the plasma sheet, i.e., high flux of cold accelerated ions (SI). The MPR spectrum has a power-law form. The small peak results from not fully separated MPR and PS plasma populations. To estimate the uncertainty related to the possibly overestimated geometrical factor below 300 eV, we calculated the difference between the integral of the measured spectra (red spectrum in Figure S2) and the test spectra presented by a light red dashed line. The test spectrum corresponds to the exact power-law spectrum in the MPR, as one would have expected, if the drop for energies below 300 eV had been due to the overestimated geometrical factor. In other words, we investigated sensitivity of the total escape flux against variation of the geometrical factor on a factor of 2 below 300 eV. The difference between the total escape fluxes is only 50%.

**Total escape over the planetary history**

To evaluate the total amount of material removed from Mars as a result of the pick-up process after the heavy bombardment was completed (later Noachian), i.e., the last 3.5Gy, we make two assumptions: (1) the current escape rate is proportional to the total content of this species in the atmosphere and (2) the escape rate is a function of the solar wind conditions. The dependence of the escape rate $Q(t)$ over time is

$$Q(t) = k \cdot M(t) \cdot SW(t),$$

where $Q(t)$ is the escape rate over age in either m/y of the global water layer for H$_2$O or bar/y for CO$_2$, $k$ a non-variable coefficient, $M(t)$ the content of the given species in the atmosphere either in m or in bar, SW(t) the function which defines the variation of the solar wind conditions with age. The important point here is the parameters, which define the solar- and solar wind conditions, such as EUV flux and solar wind mass flux, which vary with age as power-law functions (with different powers). We thus assume $SW(t)$ ~$1/t^n$, $n = 1.19$ (S2) for the solar EUV flux variation with age and $n = 2.33 \pm 0.55$ (S3) for the variation of the solar wind mass flux with age. Since it is not known what parameter(s) of the solar wind control the escape, we will estimate the total loss for a wide range of the parameter $n$ from 0 (no dependence) to $4 \approx 2.33 + 0.55 + 1.19$ (strong dependence). The variation of the total content with age is thus given by the simple equation

$$\dot{M}(t) = -K \cdot \frac{M(t)}{t^n},$$
where \( K \) is a coefficient. At the current conditions \( t = T_i \), the escape rate (measured) is \( Q_i \), the total content \( M_i \), and the equation above can be easily integrated, which gives the total loss \( \Delta M = M_0 - M_i \), \( M_0 \) is the total content at \( t = T_0 \), during the time period from \( T_0 \) to \( T_i \) as

\[
\Delta M = M_i \left( \exp \left( \frac{Q_i \cdot T_i}{M_i} - 1 \right) \right) \left( \frac{T_i}{T_0} \right)^{(n-1)} - 1
\]

(1)

To estimate the \( CO_2^+ \) loss, we use the measured \( Q_i = Q(CO_2^+) = 8 \cdot 10^{22} \text{ s}^{-1} = 4 \cdot 10^{-11} \text{ mbar/y} \). Because of the very weak current escape, the total amount of carbon dioxide removed over the 3.5 Gy period is between 0.2 – 4 mbar for the \( n \)-power range from 0 (no dependence on the solar wind conditions) to 4 (strong dependence).

\[
\Delta M(CO_2) = 0.2 – 4 \text{ mbar over 3.5 Gy}
\]

Because of the very low current escape rate, the power \( n \) is not an important parameter and it cannot within reasonable limits bring the total amount of the removed material to a range of a few bars of carbon dioxide.

We cannot calculate the total loss of water in a similar way because it is unknown what the fraction is of the escaping oxygen in the form of \( O^- \) and \( O_2^+ \) coming from the photodissociation of water. The majority of the oxygen ions come from CO\(_2\) photochemistry. However, to illustrate that the matter lost with the measured escape rates is low, we can make an upper-limit estimation assuming that all oxygen originates from photodissociation of water and is immediately lost in space. Formally, it means the escape rate \( Q(t) \) does not depend on the total content and \( Q_i = Q(O^-) + 2 Q(O_2^-) = 4.6 \cdot 10^{23} \text{ s}^{-1} = 2.67 \cdot 10^{12} \text{ m/y} \). The associated loss \( \Delta M \) is

\[
\Delta M = \frac{Q_i \cdot T_i}{(n-1)} \left( \frac{T_i}{T_2} \right)^{(n-1)} - 1
\]

(2)

The expression (2) gives \( 1 \text{ cm} \) for \( n=0 \) (no dependence on the solar wind conditions) and \( 16 \text{ cm} \) for \( n=4 \) (strong dependence). This means the total amount of water, which might have been lost through the channel in question, is below a few cm.

\[
\Delta M(H_2O) < \text{ few cm over 3.5 Gy}
\]

References and Notes


Figure S1. Spatial coverage of the measurements used in the analysis in the cylindrical coordinates (MSO, Mars – Sun – Orbit), where the x-axis corresponds to the Mars – Sun line ($X_{\text{MSO}}$) and the y-axis is the distance, $R$, to the Mars – Sun line. All distances in Martian radii, $R_m$. The figure presents the occurrence per bin (number of times the orbit passes the bin) in the volume region $-4 \, R_m < X_{\text{MSO}} < 0$ and $0 < R < 2.7 \, R_m$. The time period spans May 1, 2004 to May 30, 2006. Blue corresponds to one crossing, red (maximum) to 50 crossings per bin, black - no measurements.
Figure S2. Two-year averaged energy spectra of heavy planetary ions (O$^{+}$ + O$_2^{+}$ + CO$_2^{+}$) in the plasma sheet (PS) (blue) and in the magnetic pileup region (MPR) (red). The green line shows the one count spectrum and the vertical gray dashed line indicates the low level of validity of the geometrical factor of the instrument. Below this line, the geometrical factor was interpolated according to numerical simulations. The light red dashed line is a test spectrum used to evaluate the uncertainties.