# Solar Wind-Induced Atmospheric Erosion at Mars: First Results from ASPERA-3 on Mars Express

R. Lundin, *et al.*

*Science* **305**, 1933 (2004);
DOI: 10.1126/science.1101860

# Solar Wind–Induced Atmospheric Erosion at Mars: First Results from ASPERA-3 on Mars Express

R. Lundin,[1]* S. Barabash,[1] H. Andersson,[1] M. Holmström,[1] A. Grigoriev,[1] M. Yamauchi,[1] J.-A. Sauvaud,[2] A. Fedorov,[2] E. Budnik,[2] J.-J. Thocaven,[2] D. Winningham,[3] R. Frahm,[3] J. Scherrer,[3] J. Sharber,[3] K. Asamura,[4] H. Hayakawa,[4] A. Coates,[5] D. R. Linder,[5] C. Curtis,[6] K. C. Hsieh,[6] B. R. Sandel,[6] M. Grande,[7] M. Carter,[7] D. H. Reading,[7] H. Koskinen,[8] E. Kallio,[8] P. Riihela,[8] W. Schmidt,[8] T. Säles,[8] J. Kozyra,[9] N. Krupp,[10] J. Woch,[10] J. Luhmann,[11] S. McKenna-Lawler,[12] R. Cerulli-Irelli,[13] S. Orsini,[13] M. Maggi,[13] A. Mura,[13] A. Milillo,[13] E. Roelof,[14] D. Williams,[14] S. Livi,[14] P. Brandt,[14] P. Wurz,[15] P. Bochsler[15]

**The Analyzer of Space Plasma and Energetic Atoms (ASPERA) on board the Mars Express spacecraft found that solar wind plasma and accelerated ionospheric ions may be observed all the way down to the Mars Express pericenter of 270 kilometers above the dayside planetary surface. This is very deep in the ionosphere, implying direct exposure of the martian topside atmosphere to solar wind plasma forcing. The low-altitude penetration of solar wind plasma and the energization of ionospheric plasma may be due to solar wind irregularities or perturbations, to magnetic anomalies at Mars, or both.**

The evolution of the martian atmosphere and its possibly substantial hydrosphere is affected by interactions with the solar wind and interplanetary plasma. Various theories have been proposed to explain the change from an earlier wetter and warmer Mars (*1*). A number of processes have been suggested to explain the removal of volatiles such as $H_2O$ and $CO_2$, such as thermal (Jeans) escape, hydrodynamic escape (*2*), nonthermal escape (*3*, *4*), or catastrophic impact erosion (*5*). Jeans escape promotes mainly light ions such as hydrogen, providing mass escape rates at least an order of magnitude lower than nonthermal escape processes. Nonthermal escape (NTE) is here defined as all processes in which energization and escape of particles are related to nonthermal processes governed by solar wind forcing. Estimates of NTE have led to accumulated water volumes equivalent to a global ocean of a few meters' depth (*6*), in agreement with the Phobos-2 observations (*7*). However, Lammer *et al.* (*8*) showed that the intense extreme ultraviolet radiation and solar wind of the early Sun should lead to higher escape. They modeled an escape of water from Mars since 3.5 billion years ago equivalent to a global ocean with a thickness of ~14 to 34 m. The heavy loss of volatiles from Mars may also be associated with the lack of a strong intrinsic magnetic field like that of the Earth, which prohibits direct solar wind impact on the ionosphere and topside atmosphere (*9*).

The main objective of the ASPERA-3 experiment on Mars Express (MEX) is to study the solar wind scavenging of the ionosphere and topside atmosphere of Mars, by direct measurements of inflowing solar wind plasma and outflowing energized ionospheric plasma (the planetary wind) and by remotely imaging the flow of energetic neutral atoms (ENAs) generated by charge exchange in the exosphere of Mars. Here we focus on in situ results obtained from the electron spectrometer (ELS) and the ion mass analyzer (IMA) experiment. The ELS instrument measures electrons in the energy range 0.01 to 20 keV with high-energy resolution ($\Delta E/E = 0.07$). The IMA experiment measures ions with limited mass resolution ($m/q$ = 1, 2, 4, 8, 16, >25, where $m$ is mass and $q$ is electric charge) in the energy range 0.05 to 35 keV/$q$.

**ASPERA-3 plasma observations.** Our observations were made during the early commissioning phase of MEX, from 23 January 2004 to 22 March 2004. The induced magnetosphere boundary (IMB) is defined as the envelope of the induced martian magnetosphere, i.e., the stopping boundary for the solar wind, whereas the interior is dominated by plasma of planetary origin. We used this definition of the IMB because of the lack of magnetic field measurements on board MEX, avoiding potential conflicts with defined features such as the magnetic flux pile-up boundary (*10*). The ion data (Fig. 1) display a cyclic behavior that originates in the electrostatic elevation deflection scans versus time. The time resolution for each three-dimensional (3D) (~2π) ion distribution was ~3 min. The electron data were secured in 2D and measured in a plane with a 360° field of view. The lower ionosphere data show photoelectron lines emerging as a result of ionospheric $CO_2^+$ (Fig. 1). The photoelectron boundary (PEB) separates ionospheric electrons from shocked sheath electrons (at higher altitudes). Above the PEB and IMB, the spacecraft encounters intense fluxes of shocked solar wind ions. Finally, beyond the bow shock (BS), electrons are cooler and the solar wind ions ($H^+$ and $He^{++}$) represent cold beams.

The entire region inside the IMB is characterized by energized heavy ions accelerated up to several keV down to pericenter altitudes (~270 km). In the pass shown in Fig. 1, solar wind ions (protons) were stopped at ~500 km, i.e., at the IMB. However, because the energization of ions was observed down to the pericenter (270 km), direct solar wind forcing must also be capable of reaching these heights. The lack of complementary plasma instrumentation on MEX makes any suggested identification of the energy sources concerned very speculative. The electron data present an ordinary quiet ionosphere with only minor perturbations. This suggests low wave activity, making the energization of heavy ionospheric ions even more puzzling. Other observations of energization of ionospheric ions near the pericenter are correlated with

[1]Swedish Institute of Space Physics, Box 812, S-98 128, Kiruna, Sweden. [2]Centre d'Etude Spatiale des Rayonnements, BP-4346, F-31028 Toulouse, France. [3]Southwest Research Institute, San Antonio, TX 78228–0510, USA. [4]Institute of Space and Astronautical Science, 3-1-1 Yoshinodai, Sagamichara, Japan. [5]Mullard Space Science Laboratory, University College London, Surrey RH5 6NT, UK. [6]University of Arizona, Tucson, AZ 85721, USA. [7]Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire OX11 0QX, UK. [8]Finnish Meteorological Institute, Box 503 FIN-00101 Helsinki, Finland. [9]Space Physics Research Laboratory, University of Michigan, Ann Arbor, MI 48109–2143, USA. [10]Max-Planck-Institut für Sonnensystemforschung, D-37191 Katlenburg-Lindau, Germany. [11]Space Science Laboratory, University of California, Berkeley, CA 94720–7450, USA. [12]Space Technology Limited, National University of Ireland, Maynooth, County Kildare, Ireland. [13]Instituto di Fisica dello Spazio Interplanetari, I-00133 Rome, Italy. [14]Applied Physics Laboratory, Johns Hopkins University, Laurel, MD 20723–6099, USA. [15]University of Bern, Physikalisches Institut, CH-3012 Bern, Switzerland.

*To whom correspondence should be addressed. E-mail: rickard.lundin@irf.se

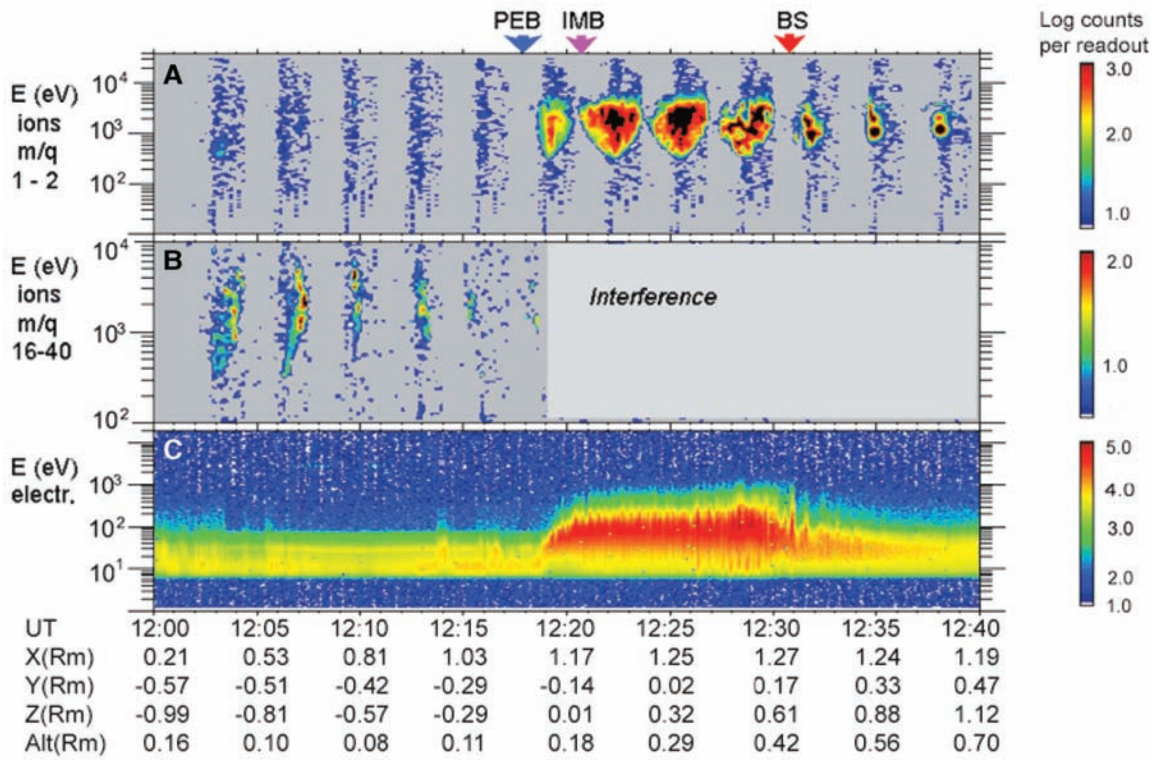


**Fig. 1.** MEX pericenter pass (~12:08 UT) traversing the ionosphere PEB, the IMB, and the BS. The three panels depict (**A**) $H^+$, (**B**) heavy ions such as $O^+$, and (**C**) electron energy-time spectra from the IMA and ELS spectrometers of ASPERA-3. "Interference" in the middle panel indicates contamination in the heavy ion mass channels by intense fluxes of $H^+$; therefore, the data there have been removed. X(Rm), Y(Rm), Z(Rm), and Alt(Rm) indicate spacecraft coordinates in the Mars solar ecliptic coordinate system. electr., electrons; Rm, Mars radii.

electron perturbations similar to those found in the sheath. Another possible energization process is solar wind electromotive forcing (such that ionospheric ions are accelerated by an externally applied solar wind electric field). Yet a third possibility is that the ions are accelerated not locally but elsewhere, perhaps upstream in the martian exosphere after being first transformed to ENAs by charge exchange (*11*, *12*). Because ENAs may propagate relatively unperturbed over long distances, possibly well away from the generation region in the exosphere, they may transform back to ions through the charge exchange process. In such a way, charge exchange could enable energized ions to, in essence, transfer to other sites, even to lower altitudes. The problem with this suggested mechanism is that the expected fluxes should be rather low, whereas the heavy ion fluxes actually recorded are very high.

The composition of energized ionospheric ions reflects the source altitude of the ions (*13*). On 27 February 2004, we measured $H^+$ with several keV together with ~700-eV heavy ions ($O^+$ and molecular ions, possibly $O_2^+$) at an altitude of ~290 km (Fig. 2A). The intense $H^+$ ion flux suggests a solar wind origin, illustrating that solar wind ions may intrude down to an altitude of ~290 km in the dayside martian ionosphere. Figure 2B (25 January 2004) shows a strong peak at $m/q$ ~ 2 with energy of ~4 keV, in addition to energized heavy ions ($O^+$) of ~500 eV. Normally, $m/q = 2$ is associated with solar wind $He^{++}$, but a lack of the dominant solar wind species, protons, suggests either that the protons were "removed" (possibly through charge exchange), leaving $He^{++}$ essentially unaffected, or that the peak corresponds to martian $D^+$ or $H_2^+$. Because the altitude is 900 km, we can immediately exclude the possibility of proton removal by charge exchange. The relatively high flux, of the order $10^6$ (cm$^2$ s steradian keV)$^{-1}$, excludes $D^+$, leaving us with the final possibility, that the peak is due to $H_2^+$. If this is correct, it implies energization and upward transport of $H_2^+$ from relatively low altitudes where the ionospheric temperatures are lower. Low-energy ionized molecular hydrogen was found by the ASPERA experiment on Phobos-2 (*14*) near Phobos, a moon of Mars, possibly as a result of outgassing. However, the quite high energy of the MEX $m/q = 2$ peak is puzzling. We are therefore faced with the possibility that the $m/q$ peak is due to $He^{++}$, while still lacking a good explanation for the dearth of protons. The strong energization of heavy ions (predominantly $O^+$) at an altitude of ~330 km (Fig. 2C) results in a relatively broad energy distribution, ~1 to 5 keV, quite different from the heavy ion acceleration in Fig. 2, A and B. From the energy distribution point of view, this resem-

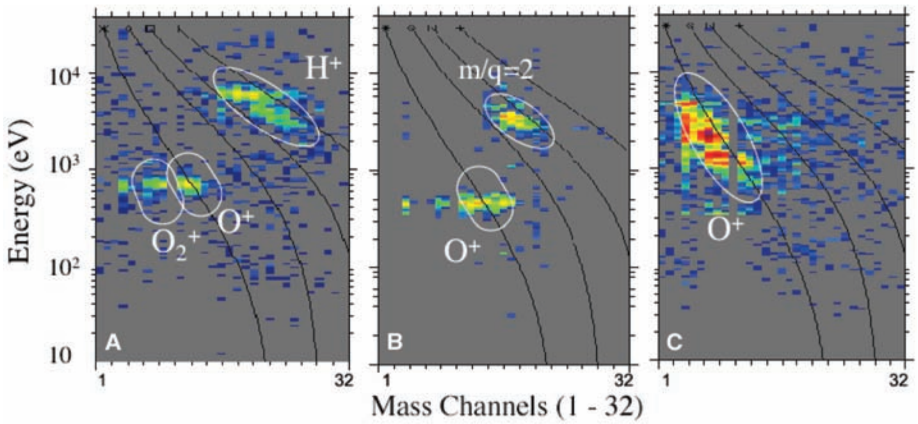


**Fig. 2.** Three examples of energy-$m/q$ spectra for energized ions. Skewed lines indicate nominal mass identifications for $m/q$ of 1, 2, 4, and 16, respectively. (**A**) 27 February 2004, 2- to 7-keV $H^+$ and ~700-eV heavy ions ($O^+$ and $O_2^+$) at an altitude of ~290 km. (**B**) 25 January 2004, ~500-eV heavy ions and keV ions with $m/q = 2$ (possibly $He^{++}$, $H_2^+$, and $D^+$) at an altitude of 900 km. (**C**) 22 March 2004, strong energization of heavy ions at an altitude of ~330 km.

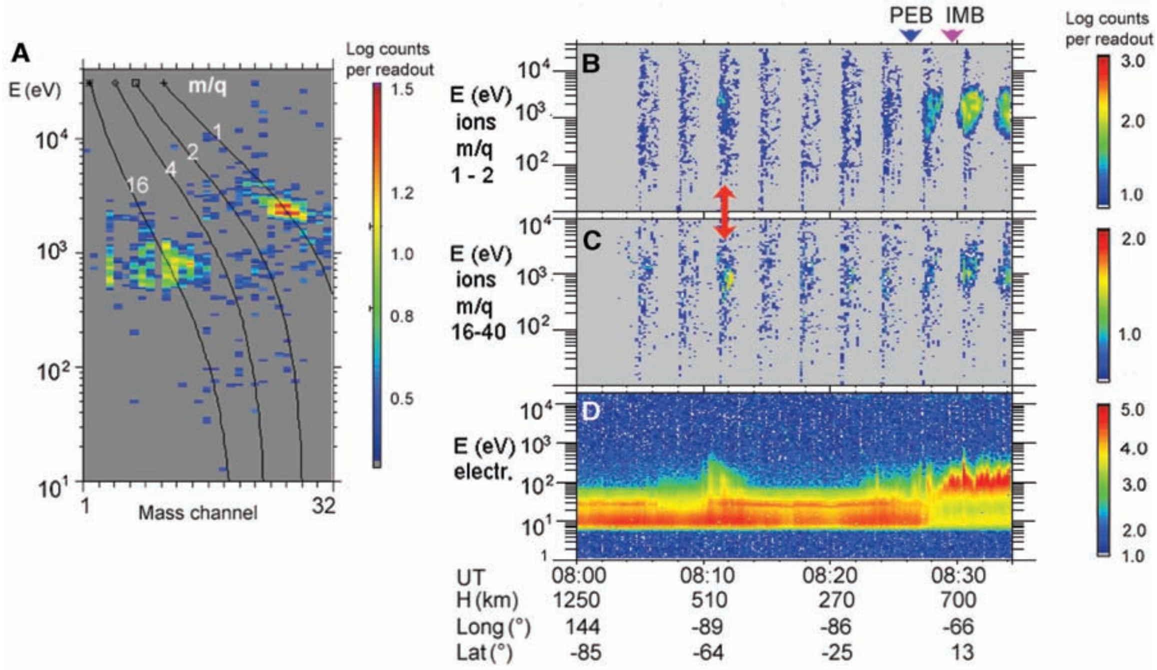


**Fig. 3.** Spectra for 1 March 2004, showing energized heavy ions (~0.8 to 1 keV) and electrons at an altitude of ~460 km, simultaneously with $H^+$ (~2 keV) of solar wind origin. (**A**) An energy-mass spectrum of the event marked by the red double arrow in (B) and (C) (08:10 to 08:13 UT). (**B** to **D**) Energy-time spectra for (B) $H^+$ and $He^{++}$, (C) heavy ions, $m/q > 16$, and (D) electrons. H, height; Long, longitude; Lat, latitude.

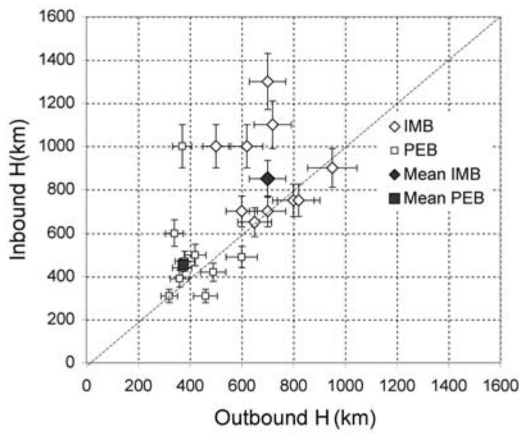


**Fig. 4.** Altitude statistics for the dayside martian PEB and IMB. To illustrate the variability (in space and time) of the boundaries, the inbound boundary altitude is plotted versus the outbound boundary altitude.

bles transverse (to the ambient magnetic field) energization of ionospheric plasma in the terrestrial upper ionosphere. However, in the absence of magnetic field data, we can only conclude that the heavy ions flow as in the external sheath. We noted previously that the electron data show low wave activity, suggesting that the energization is nonlocal, possibly resulting from upstream activities.

On 1 March 2004, we observed a more typical case of local plasma energization, i.e., energization of heavy ions associated with sheathlike or energized electrons (~08:10 UT) (Fig. 3). This energization was separated from the ambient ionospheric electrons, at altitudes that imply the PEB is not stable versus time. We also observed an almost identical, well-separated electron perturbation that occurred simultaneously at Mars Global Surveyor (MGS), when the spacecraft were separated by ~1800 km. This implies a temporal phenomenon, most likely a consequence of a solar wind perturbation. Consequently, solar wind irregularities may have a strong impact not only on the location of the PEB and IMB plasma boundaries, but also on the energization and escape of ionospheric plasma at Mars. This isolated event occurred geographically well away from magnetic anomalies at Mars, although we also observed cases above magnetic anomalies like on MGS (*15*, *16*). However, the dayside magnetic field well above an anomaly is perturbed by the external (sheath) magnetic field, so the connection to the low-altitude magnetic anomaly is not trivial. For instance, the magnetic flux tube of an anomaly is swept tailward by the solar wind interaction. Therefore, what appears to be ion energization over a region void of magnetic anomalies may in fact be due to energization processes over a magnetic anomaly further upstream. Our preliminary results are therefore inconclusive with regard to the magnetic anomalies and ionospheric ion energization.

The altitude statistics of the dayside martian PEB and IMB were determined by combining ion and electron data (Fig. 4). We used the lower end of the photoelectron transition region for the PEB, and the upper bound of the region where sheath plasma (ions and electrons) strongly decreases inward as the IMB. The IMB is consistent with the boundaries inferred from Phobos-2 data and given various names such as ‘‘magnetopause’’ or ‘‘planetopause’’ (*7*, *17*). The IMB marks the stopping boundary for sheath electrons, thereby resembling the magnetic flux pile-up boundary (*10*). Inbound traversals were plotted versus outbound traversals to illustrate the temporal and spatial variability of the boundaries. During our study period, MEX inbound traversals of the IMB occurred in the prenoon sector at clock angles ~330° to 350° in the early period and ~260° to 280° in the later period. The corresponding outbound clock angles of the IMB were ~30° to 50° and ~0° to 15°, respectively. This implies a stronger inbound-outbound asymmetry with respect to the noon meridian in the later period. The mean values for inbound and outbound traversals are 455 km (in) and 375 km (out) for the PEB and 850 km (in) and 700 km (out) for the IMB; i.e., there is a slight asymmetry with higher IMB and PEB altitudes for inbound crossings. The mean IMB and PEB asymmetry is probably related to tailward magnetosphere flaring. The varying heights of the IMB and PEB along the symmetry line may correspond to slow variations of the solar wind dynamic pressure. However, the fine structure in Fig. 4 and, in particular, observations of multiple boundary crossings demonstrate the variability of the solar wind penetration process and also the lack of stability of the boundaries.

Table 1 gives some preliminary statistics of the solar wind ion access and the ionospheric ion energization inside the PEB and IMB. We binned the number of measurement sequences (~3 min) in which solar wind ions were observed inside the IMB and in which solar wind ion fluxes were below the measurement threshold. In a similar manner, the number of sequences with or without energized ionospheric ions inside the IMB and PEB, respectively, was determined. The dayside IMB is not a rigid boundary for solar wind ions. In about half of the cases, we observed solar wind ions at altitudes lower than where the IMB should have been, according to the electron data. We observed accelerated ionospheric ions well inside the IMB and sometimes also inside the PEB.

Localized precipitation of solar wind ions and the energization and erosion of ionospheric ions deep inside the ionosphere (Fig. 5 and Table 1) illustrate the variability of the dayside ionosphere at Mars. The mean PEB and IMB boundaries represent average states of the dayside ionosphere. The combined solar wind plasma precipitation and energization of ionospheric plasma suggests a rather corrugated ionosphere at Mars, with strong depletion zones that may vary with time scales on the order of a few minutes. The high variability of the IMB and PEB may be due to ionospheric peak thermal pressure insufficient to withhold the solar wind ram pressure (*18*), combined with external forcing instabilities such as the Kelvin-Helmholtz instability.

**Discussion.** We have presented ASPERA-3 observations of ions and electrons from the first two months of MEX commissioning near Mars, focusing on data from pericenter passes in the noon/postnoon meridian. On the basis of 11 pericenter passes, we summarize our findings as follows:

1) Solar wind plasma protrudes fairly deep into the martian ionosphere and atmosphere, occasionally down to pericenter altitudes ~270 km above the surface of Mars.

2) Acceleration processes responsible for the erosion and loss of the martian ionosphere may go deep down in the ionosphere, with the planetary wind from the dayside region sweeping tailward at altitudes as low as ~270 km.

3) Accelerated or outflowing heavy ions (e.g., $O^+$) with several keV in energy are found at 300 km in altitude.

4) The planetary wind also comprises molecular species, mainly as heavy ion molecules (e.g., $CO_2^+$ and $O_2^+$). This is consistent with ionospheric ion energization processes that reach low altitudes.

These findings raise a number of questions regarding ionospheric escape processes at Mars. Solar wind forcing extending deep into the ionosphere agrees with the Viking 2 lander results; the Viking 2 entry into the ionosphere displayed a sharp density cutoff above ~300 km in altitude (*13*). ASPERA-3 data show that energization and erosion of ionospheric plasma may even start below 300 km, at heights with high densities of molecular ions (*19*). Our ASPERA-3 data also confirm previous findings from Phobos-2 of molecular ions (*7*, *14*). The origin of escaping ions is related to the upper atmosphere photochemistry at Mars. The origin of, for example, escaping $O^+$ ions (possibly from $CO_2$ or $H_2O$) is not clear. However, the main origin of atmospheric hydrogen must be water. The combined escape of $H^+$ and $O^+$, as evidenced by measurements in the central plasma tail by Phobos-2 (*17*), is therefore evidence for a slow dehydration of Mars.

The composition of the heavy molecular ions is a matter for further investigation. For instance, how much of the escaping molecular ions are $O_2^+$ and how much are $CO_2^+$? Considering that the dominant atmospheric constituent is $CO_2$, it is important to establish the loss rate of carbon from the martian atmosphere. At this early stage, we cannot exclude that a large fraction of the molecular ion outflow is $CO_2^+$ and $CO^+$. It will be difficult to separate $C^+$ from $O^+$ with IMA, making it hard to shed light on the carbon loss issue. Hot carbon densities in the exosphere have been discussed by Nagy *et al.* (*20*), who note that the outflow of carbon may be substantial during high solar activity.

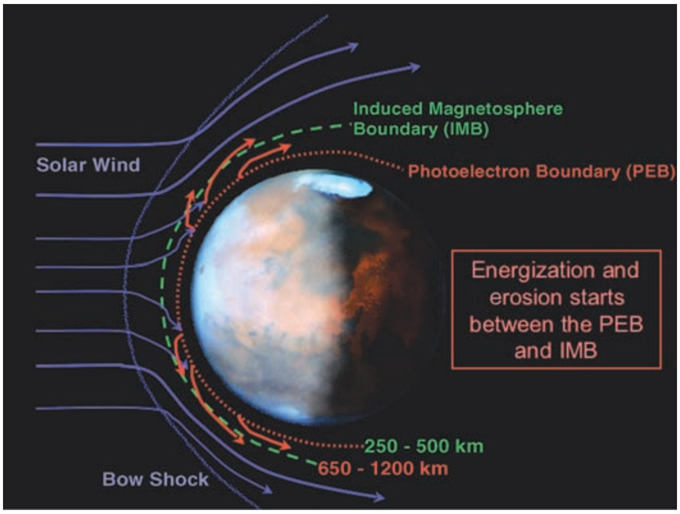


**Fig. 5.** Diagram illustrating ASPERA-3 findings of the solar wind–induced planetary ion erosion from the dayside ionosphere of Mars, showing how planetary ions pick up speed at altitudes located between the PEB and the IMB.

**Table 1.** Preliminary statistics of ASPERA-3 pericenter data.

| | Solar wind ions and IMB | Accelerated ions and IMB | Accelerated ions and PEB |
|---|---|---|---|
| Inside the boundary | 37 | 33 | 13 |
| Outside the boundary | 38 | 42 | 28 |

**References and Notes**

1. R. Kerr, *Science* **289**, 714 (2000).
2. E. Chassifiere, *Icarus* **124**, 537 (1996).
3. H. Pérez-de-Tejada, *J. Geophys. Res.* **92**, 4713 (1987).
4. J. G. Luhmann, S. J. Bauer, *Geophys. Monogr. Am. Geophys. Union* **66**, 417 (1992).
5. H. J. Melosh, A. M. Vickery, *Nature* **338**, 487 (1989).
6. H. Pérez-de-Tejada, *J. Geophys. Res.* **103**, 31499 (1998).
7. R. Lundin *et al.*, *Nature* **341**, 609 (1989).
8. H. Lammer *et al.*, *Int. J. Astrobiol.* **2**, 195 (2003).
9. R. Lundin, *Science* **291**, 1909 (2001).
10. D. Vignes *et al.*, *Geophys. Res. Lett.* **27**, 49 (2000).
11. S. R. Barabash *et al.*, in *Mars Express: The Scientific Payload*, A. Wilson, Ed. (ESA Special Publication SP-1240, 2004); available at http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=34885.
12. M. Holmström, S. Barabash, E. Kallio, *J. Geophys. Res.* **107**, 1029 (2002).
13. W. B. Hanson, S. Sanatani, D. R. Zuccaro, *J. Geophys. Res.* **82**, 4351 (1977).
14. O. Norberg, R. Lundin, S. Barabash, in *Proceedings of the COSPAR Colloquium 4*, T. I. Gombosi, Ed. (Elsevier, Oxford, 1992), pp. 299–304.
15. M. J. Acuña *et al.*, *Science* **284**, 790 (1999).
16. D. L. Mitchell *et al.*, *J. Geophys. Res.* **106**, 23419 (2001).
17. R. Lundin *et al.*, *Geophys. Res. Lett.* **17**, 873 (1990).
18. J. G. Luhmann, C. T. Russell, F. L. Scarf, L. H. Brace, W. C. Knudsen, *J. Geophys. Res.* **92**, 8545 (1987).
19. M. B. McElroy, T. Y. Kong, Y. L. Yung, *J. Geophys. Res.* **82**, 4379 (1977).
20. A. F. Nagy, M. W. Liemohn, J. L. Fox, *J. Geophys. Res.* **106**, 21565 (2001).
21. The ASPERA-3 experiment on the European Space Agency (ESA) Mars Express is a joint effort among 15 laboratories in 10 countries, all supported by their national agencies. We thank all these agencies, as well as the various departments and institutes hosting these efforts. We wish to acknowledge in particular the Swedish National Space Board and NASA for their support of the Swedish Institute of Space Physics. We are indebted to the ESA for their courage in embarking on MEX, the first ESA mission to the Red Planet.

23 June 2004; accepted 20 August 2004