PERSPECTIVES: PLANETARY SCIENCE

Erosion by the Solar Wind

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The planets in our solar system are exposed to a variable but persistent bombardment by the expanding solar corona, the solar wind. The closer to the sun, the more intense is the flux of solar protons, electrons, and alpha particles that make up the solar wind. The Earthlike planets—Mercury, Venus, Earth, and Mars—are thus the ones most affected by the solar wind. The power per unit area of the solar wind is some six orders of magnitude less than that of the solar electromagnetic radiation, but the solar wind is much more effective in removing planetary atmospheres. Why, then, is there so little loss from Earth, as Seki *et al.* report on page 1939 of this issue (*1*)?

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The net loss of matter from Earthlike planets depends on the balance between inflow and outflow. The stronger the gravitation, the more difficult it is for matter to escape (*2*). Small objects thus loose matter—especially volatiles like water and carbon dioxide—much more readily. This is apparent when a comet approaches the sun. The comet expands into a spectacular gaseous object visible in the night sky, although its core is only a few kilometers in diameter. A careful look at a comet shows that it has two tails (see the figure): a diffuse shorter tail formed by debris and neutral gas along the cometary orbit, and a blue-green, elongated, very structured tail (*3*) maintained by the interaction of the solar wind with the expanding cometary gas, which gets ionized and accelerated to very high speeds.

These two cometary tails illustrate the two solar-induced atmospheric erosion processes—thermal or Jeans escape and nonthermal plasma escape. In a low-gravity environment close to the sun, thermal escape may be the major loss process, but in a strong-gravity environment it is usually less important, except for Mercury, which orbits very close to the sun. The erosion of most planetary atmospheres is thus dominated by nonthermal escape. Like comets, planets have extended, highly structured plasma tails, but the rate of erosion is much lower and the planetary tails in our solar system are invisible to ground-based optical telescopes.

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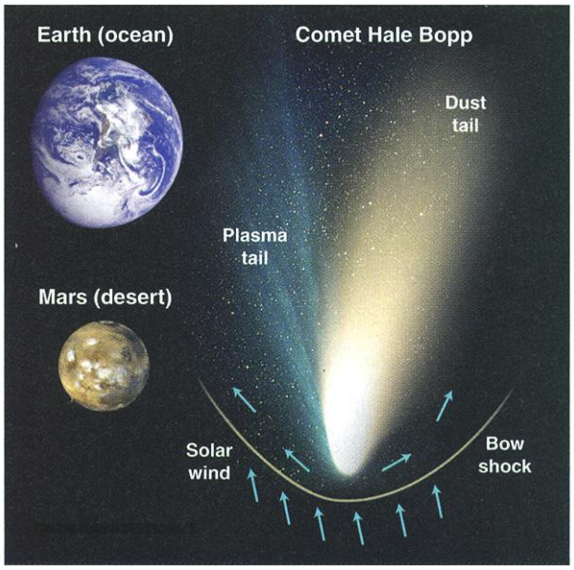
Today, Earth looses matter at a rate of 1 to 3 kg/s (*4*), the rate and composition varying with solar cycle. Seki *et al.* (*1*) claim that the loss is even lower. However, even with a net loss of 3 kg/s, it would take 50 billion years to deplete Earth's atmosphere and at least another 15 trillion years to evacuate the oceans. For comparison, the total lifetime of the sun is only about 10 billion years.



The solar wind takes its toll. Interaction with the solar wind leads to erosion of volatiles such as water from celestial objects such as comets in near solar orbit. Water may be retained on a "shielded" planet (Earth) but erodes faster from unshielded objects like comets and Mars.

SOURCES: EARTH AND MARS/NASA; HALE-BOPP, A. DIMAI, R. VOLCAN, D.GHIRARDO/COL DRUSCIE OBS., ACC

Loss processes may account for differences in atmospheric and surface properties between the Earthlike planets. Earth is the only planet covered with oceans. Venus has an extremely hot and dense atmosphere. Mars may have had a hydrosphere in the past but is bare today. If the four Earthlike planets aggregated from the same dust cloud in the early solar nebula, which seems likely given their similar mass density and core properties, why did they evolve in such a different way?

An important part of the answer is that there was, and is, a substantial difference in the rate of atmospheric and hydrospheric erosion between the planets. Mercury, the smallest of the planets and the closest to the sun, is essentially void of volatiles, which have been eroded away by the intense heat and solar wind close to the sun. Earth has a strong intrinsic magnetic field that fends off the solar wind well outside the atmosphere. The small losses reported by Seki *et al.* (*1*) strengthen the hypothesis that the magnetic field acts as a shield to solar wind erosion. Venus and Mars both lack an intrinsic magnetic field, and their interaction with the solar wind resembles that of comets.

Little or no water is present on Venus and Mars today. We know very little about atmospheric escape from Venus, but recent data from Mars (*5*) confirm theories of a wet early Mars. It may thus have been habitable, discrediting the hypothesis of a favorable "life zone" at exactly the sun-Earth distance. Atmospheric escape from Mars is about 1 kg/s (*6*). At this rate, Mars may have had an average water cover of a few meters some 4 billion years ago. Simple calculations (*7*) suggest, however, that an early denser, warmer, more humid atmosphere may have had an erosion rate more than 10 times higher than that of today. If so, Mars may have been covered with oceans. Recent observations (*8*) suggest that Mars once had an intrinsic magnetic dynamo, but this shield apparently disappeared several billion years ago, leaving the planet vulnerable to cometlike loss.

The differences in atmospheric content between the Earthlike planets and the unique capability of Earth to retain its hydrosphere are still hotly debated among space scientists. However, nonthermal escape induced by interaction with the solar wind is now recognized as a major loss process. Assuming no chemical differences between the Earthlike planets during formation, an important requirement for an Earthlike planet to retain its atmosphere and hydrosphere is thus to have a protection mechanism against the eroding solar wind. A strong intrinsic magnetic dynamo, like that of Earth, appears to help.

References and Notes

1. K. Seki, R. C. Elphic, M. Hirahara, T. Terasawa, T. Mukai, *Science* **291**, 1939 (2001).
2. The velocity required for matter to escape the gravitational field is 11.4 km/s for Earth, 5.0 km/s for Mars, 4.3 km/s for Mercury, and only a few meters per second for a comet.
3. This tail is sometimes referred to as the "ion tail" but should be denoted a plasma tail because it contains an equal amount of ions and electrons.
4. C. R. Chappell, T. E. Moore, J. H. Waite Jr., *J. Geophys. Res.* **92**, 5896 (1987).
5. R. Kerr, *Science* **289**, 714 (2000).
6. R. A. Lundin *et al.*, *Nature* **341**, 609 (1989).
7. H. Pérez-de-Tejada, *J. Geophys. Res.* **92**, 4713 (1987).
8. M. J. Acuna *et al.*, *Science* **284**, 790 (1999).