How did Mars lose its atmosphere and water? FREE

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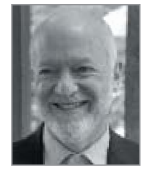

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Mars today is a cold, dry planet. Its temperature averages 50 K below the freezing point of water. And its atmosphere is too thin for water to persist as a liquid. Geological evidence, however, shows that liquid water was abundant on the surface of ancient Mars (see my article with Michael Mellon, Physics Today, April 2004, page 71). The planet has features that imply the existence of rivers, streams, and shorelines early in Mars's history (see figure 1).

The Sun was 30% dimmer then, so a thick greenhouse atmosphere must have been warming the planet. Carbon dioxide makes up 96% of today's atmosphere and was likely the largest contributor to that greenhouse effect, though it may not have been the only greenhouse gas on Mars. Where did the CO_2 from that earlier, thicker atmosphere go? Where did the water that carved the channels and eroded the surface go? Can water and CO_2 be put back into the atmosphere and make Mars warm again?

It takes no more than a few bars of pressure from atmospheric CO_2 to raise the temperature to the melting point of ice, and Mars initially may have had as much as 20 bars. By comparison, the total atmospheric pressure at Earth's surface is about 1 bar. The abundance of water on Mars can be expressed as a global equivalent layer (GEL), which is the depth of the water if all of it existed at the surface as a liquid and was spread uniformly over the planet. Mars's observed morphological features would have required a GEL of at least 50 m. Water may also reside as groundwater or as ice in the crust, in an amount that could raise the GEL by nearly an order of magnitude. Altogether, those reservoirs yield about 500 m GEL of water on the planet. By comparison, Earth's oceans, if spread over the entire planet, would form a layer about 2 km thick.

MAVEN

Planets can lose water and CO_2 above their surfaces in two ways. The Sun and its solar wind can strip water vapor and gaseous CO_2 from the top of the atmosphere into space. The two compounds can also diffuse into the subsurface. There, CO_2 and water can react with crustal materials to form CO_2- and H_2O-rich minerals.

The *Mars Atmosphere and Volatile Evolution*, or *MAVEN*, spacecraft has been tracking the stripping of the Martian atmosphere since 2014. Although the atmosphere is losing gas today at a rate of only about 2–3 kg/s, rates would have been much higher early in Mars's history, when the Sun's extreme UV rays and the solar wind were more intense. But by observ-

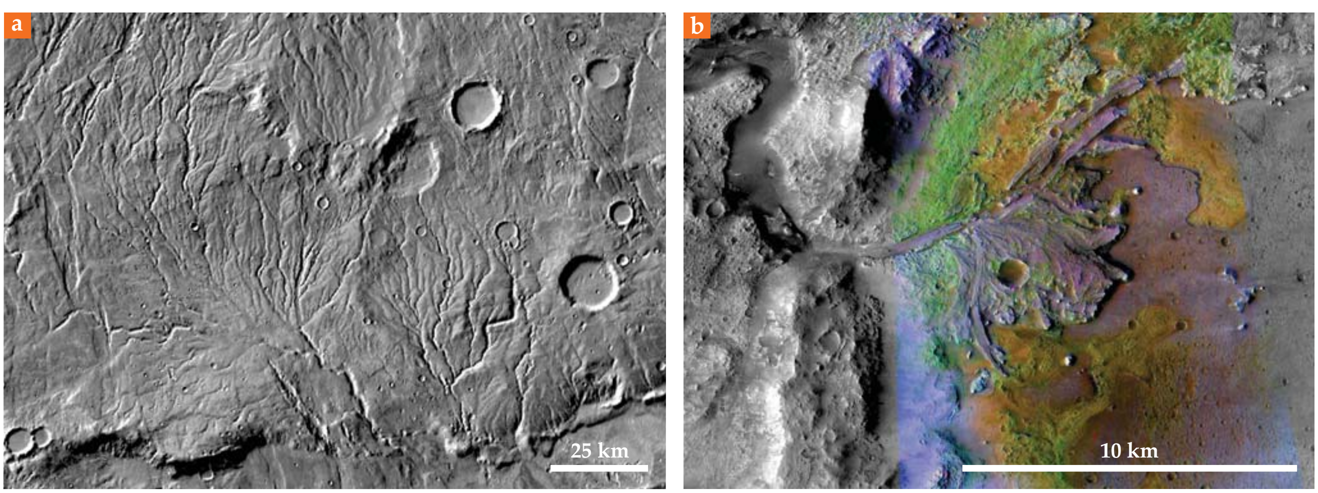

FIGURE 1. GEOLOGICAL EVIDENCE for the presence of liquid water on ancient Mars. **(a)** Valley networks on the oldest surfaces are thought to have been carved gradually by stable liquid water. **(b)** A river delta formed from debris deposited where water flowed into Jezero Crater. Colors represent compositional information derived from orbital spectroscopy that relates to water-bearing minerals. (Courtesy of NASA.)

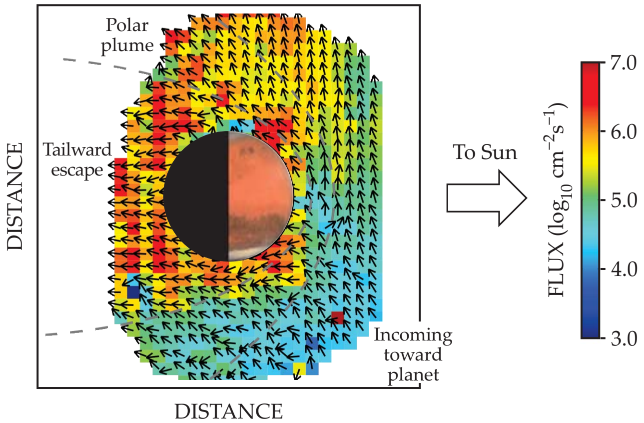

FIGURE 2. A YEAR'S WORTH of data on oxygen escaping from Mars. Colors represent the flux of oxygen atoms, and arrows show the average direction of their movement. (Adapted from an image courtesy of the American Geophysical Union.)

ing the processes today and knowing some history of the Sun, planetary scientists can extrapolate the loss rate into the past and estimate the total loss through time.

They use the observed enrichment of the heavier of stable isotope pairs, such as D/H, $^{13}C/^{12}C$, $^{15}N/^{14}N$, and $^{38}Ar/^{36}Ar$, to infer the fraction of each gas that has been lost (see Physics Today, May 2015, page 12). In each case, the lighter isotope is removed to space more easily and leaves behind an increased concentration of the heavier isotope.

Loss of hydrogen, oxygen, and carbon are of interest to scientists because of their connections to the climate-related gases H_2O and CO_2. Using the measurements of *MAVEN* and other spacecraft, for example, researchers can track H atoms from their occurrence in atmospheric water vapor in the lower atmosphere to an extended corona that reaches from the upper atmosphere to at least as far as 10 Mars radii.

The inferred H loss rate varies by as much as an order of magnitude through the Martian seasons. That variation results from increased atmospheric dust near perihelion that raises temperatures and allows water to be carried to higher altitudes where it can escape more readily. Extrapolating the loss through time, scientists have found that more than 25 m GEL of H_2O may have been lost to space.

Scientists can also track the historical loss of O to space by recognizing that it can come from either CO_2 or H_2O. Oxygen is removed either as ions from the upper atmosphere or by photochemical processes that break up CO_2 or H_2O and eject the O atom (see figure 2). Carbon is harder to track, but researchers can estimate the total amount lost to space from the $^{13}C/^{12}C$ isotope ratio, from the current estimated loss rate for O, and from the rate of photodissociation and loss of atmospheric carbon monoxide. Those amounts yield an integrated loss through time of at least 1–2 bars of CO_2.

The dynamo, reactions, and the poles

Planetary scientists think that the loss of H was much larger early in history when the Sun's UV radiation intensity was much higher. The stripping of C and O by the solar wind began about 4.1 billion years ago, when the Martian magnetic field shut off with the death of the planet's dynamo (see Physics Today, October 2021, page 17). At that point in time, no global magnetic field existed to protect the atmosphere from the onslaught of the solar wind.

Carbon dioxide can react with minerals to form carbon-bearing minerals in the crust. Orbital surveys have identified it in surface materials, in buried materials that have been exposed at the surface, and in meteorites found on Earth that have come from Mars. Carbonates at or near the surface hold the equivalent of no more than a couple of tens of millibars of CO_2—counted as if it all were released into the atmosphere. Deeply buried carbonates could hold up to a bar of CO_2, but their abundance is difficult to quantify, as they are exposed and visible in only a few locations.

Today, water is locked up in the polar caps and in mid- and high-latitude ground ice. Those sinks hold about 20–30 m GEL of H_2O. A much bigger sink may be water bound in hydrated minerals at the surface that spacecraft have identified spectroscopically from orbit.

Scientists can extrapolate that data to estimate the water locked up in the minerals hidden beneath the surface, but with large uncertainties. The most likely amount of stored water is between 130–260 m GEL, although a reservoir more than 500 m deep is possible. The large uncertainty arises from the difficulty of predicting a global abundance from a small number of exposures of minerals.

Clearly, the removal of CO_2 from the atmosphere to space and the crust can account for the loss of a thick early atmosphere. But the water history is more complicated. In addition to being lost to space and the crust, water has been released to the surface in catastrophic floods. That water would have eventually evaporated over time or percolated into the crust, and volcanic materials would have outgassed. Today H_2O from the polar ice caps moves through the atmosphere and exchanges with midlatitude ground ice or condenses at the opposite pole. The amounts of water in each case are difficult to quantify. Despite the uncertainties, however, scientists are getting a consistent story of what drove the evolving climate and water on Mars.

Can the CO_2 that is locked in the crust be mobilized and restored to Mars's atmosphere today? If that were possible, it could support greenhouse warming that would raise the planet's temperature and allow liquid water to become widespread again. Unfortunately, the bulk of the CO_2 that remains on Mars is distributed globally and would require strip-mining and processing of the entire planet to release.

Don't give up hope, though. One can imagine manufacturing boutique, high-efficiency greenhouse gases on Mars that could—someday, at least—provide a substantial greenhouse effect.

Additional resources

▶ M. S. Chaffin et al., "Martian water loss to space enhanced by regional dust storms," *Nat. Astron.* **5**, 1036 (2021).
▶ J. P. Grotzinger et al., "A habitable fluvio-lacustrine environment at Yellowknife Bay, Gale Crater, Mars," *Science* **343**, 1242777 (2014).
▶ B. M. Jakosky, "The CO_2 inventory on Mars," *Planet. Space Sci.* **175**, 52 (2019).
▶ B. M. Jakosky, "Atmospheric loss to space and the history of water on Mars," *Annu. Rev. Earth Planet. Sci.* **49**, 71 (2021).
▶ R. D. Wordsworth, "The climate of early Mars," *Annu. Rev. Earth Planet. Sci.* **44**, 381 (2016). PT