The Planetary Air Leak

As Earth's atmosphere slowly trickles away into space, will our planet come to look like Venus?

By David C. Catling and Kevin J. Zahnle

KEY CONCEPTS

- Many of the gases that make up Earth's atmosphere and those of the other planets are slowly leaking into space. Hot gases, especially light ones, evaporate away; chemical reactions and particle collisions eject atoms and molecules; and asteroids and comets occasionally blast out chunks of atmosphere.
- This leakage explains many of the solar system's mysteries. For instance, Mars is red because its water vapor got broken down into hydrogen and oxygen, the hydrogen drifted away, and the surplus oxygen oxidized—in essence, rusted—the rocks. A similar process on Venus let carbon dioxide build up into a thick ocean of air; ironically, Venus's huge atmosphere is the result of the *loss* of gases.

—The Editors

One of the most remarkable features of the solar system is the variety of planetary atmospheres. Earth and Venus are of comparable size and mass, yet the surface of Venus bakes at 460 degrees Celsius under an ocean of carbon dioxide that bears down with the weight of a kilometer of water. Callisto and Titan—planet-size moons of Jupiter and Saturn, respectively—are nearly the same size, yet Titan has a nitrogen-rich atmosphere thicker than our own, whereas Callisto is essentially airless. What causes such extremes? If we knew, it would help explain why Earth teems with life while its planetary siblings appear to be dead. Knowing how atmospheres evolve is also essential to determining which planets beyond our solar system might be habitable.

A planet can acquire a gaseous cloak in many ways: it can release vapors from its interior, it can capture volatile materials from comets and asteroids when they strike, and its gravity can pull in gases from interplanetary space. But planetary scientists have begun to appreciate that the escape of gases plays as big a role as the supply. Although Earth's atmosphere may seem as permanent as the rocks, it gradually leaks back into space. The loss rate is currently tiny, only about three kilograms of hydrogen and 50 grams of helium (the two lightest gases) per second, but even that trickle can be significant over geologic time, and the rate was probably once much higher. As Benjamin Franklin wrote, "A small leak can sink a great ship." The atmospheres of terrestrial planets and outer-planet satellites we see today are like the ruins of medieval castles—remnants of riches that have been subject to histories of plunder and decay. The atmospheres of smaller bodies are more like crude forts, poorly defended and extremely vulnerable.

Recognizing the importance of atmospheric escape changes our perspective on the solar system. For decades, scientists have pondered why Mars has such a thin atmosphere, but now we wonder: Why does it have any atmosphere left at all? Is the difference between Titan and Callisto a consequence of Callisto's losing its atmosphere, rather than of Titan having been born of airier stuff? Was Titan's atmosphere once even thicker than it is today? How did Venus steadfastly cling to its nitrogen and carbon dioxide yet thoroughly lose its water? Did escape of hydrogen help to set the stage for complex life on Earth? Will it one day turn our planet into another Venus?

When the Heat Is On

A spaceship that reaches escape velocity is moving fast enough to break free of a planet's gravity. The same is true of atoms and molecules, although they usually reach escape velocity less purposefully. In thermal escape, gases get too hot to hold on to. In nonthermal processes, chemical or charged-particle reactions hurl out atoms and molecules. And in a third process, asteroid and comet impacts blast away the air.

Thermal escape is, in some ways, the most common and straightforward of the three. All bodies in the solar system are heated by sunlight. They rid themselves of this heat in two ways: by emitting infrared radiation and by shedding matter. In long-lived bodies such as Earth, the former

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LOSS OF CERTAIN GASES, especially hydrogen, has transformed Earth. It is one of the reasons that oxygen built up in the atmosphere. In the future, the depletion of hydrogen will dry out our oceans and all but shut down geologic cycles that stabilize the climate. Life may still be able to hold out in the polar regions.

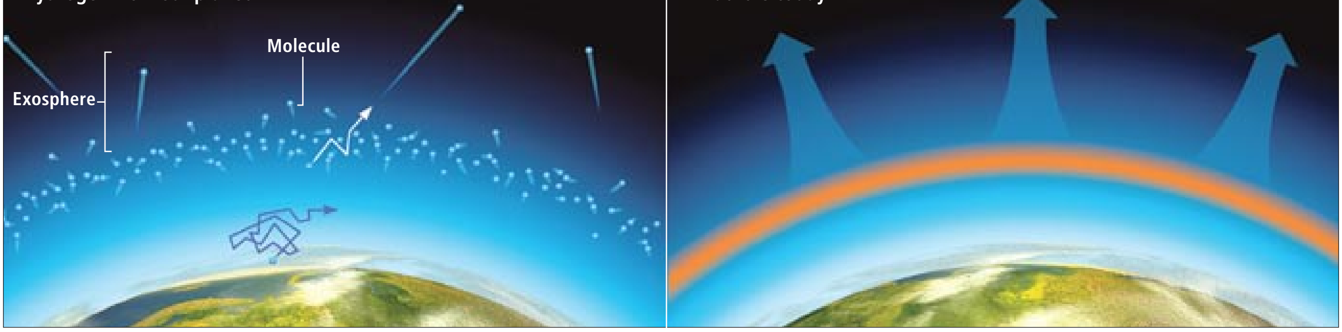
[ESCAPE MECHANISM #1]

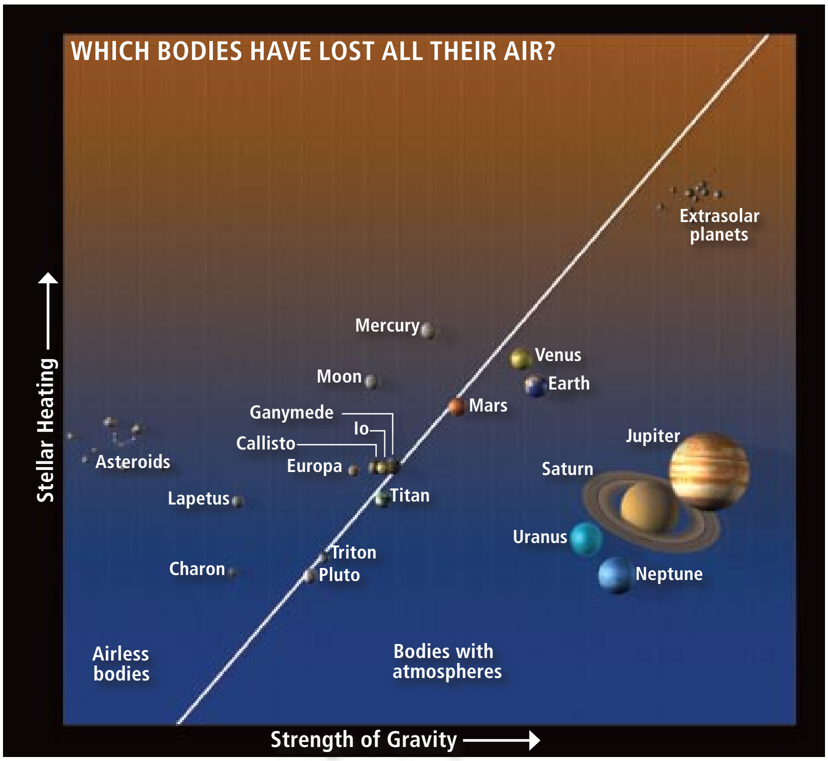
PLANETARY TEAKETTLE

One major cause of air loss is solar heating. Heat can drive out air in one of two ways.

AIR EVAPORATES MOLECULE BY MOLECULE
In an atmosphere's uppermost layer, or exosphere, nothing stops the fastest-moving atoms and molecules from flying off into space. This process, known as Jeans escape, accounts for much of the leakage of hydrogen from our planet.

HEATED AIR FLOWS OUT IN A WIND
Air heated by sunlight rises, accelerates and attains escape velocity. This process, known as hydrodynamic escape, was particularly important on early Earth and Venus—in fact, it may be why Venus became what it is today.





EVIDENCE FOR THERMAL ESCAPE comes from considering which planets and satellites have atmospheres and which do not. The deciding factor appears to be the strength of stellar heating (*vertical axis*) relative to the strength of a body's gravity (*horizontal axis*). Airless worlds have strong heating and weak gravity (*left of line*). Bodies with atmospheres have weak heating and strong gravity (*right of line*).

process prevails; for others, such as comets, the latter dominates. Even a body the size of Earth can heat up quickly if absorption and radiation get out of balance, and its atmosphere—which typically has very little mass compared with the rest of the planet—can slough off in a cosmic instant. Our solar system is littered with airless bodies, and thermal escape seems to be a common culprit. Airless bodies stand out as those where solar heating exceeds a certain threshold, which depends on the strength of the body's gravity [*see illustration above*].

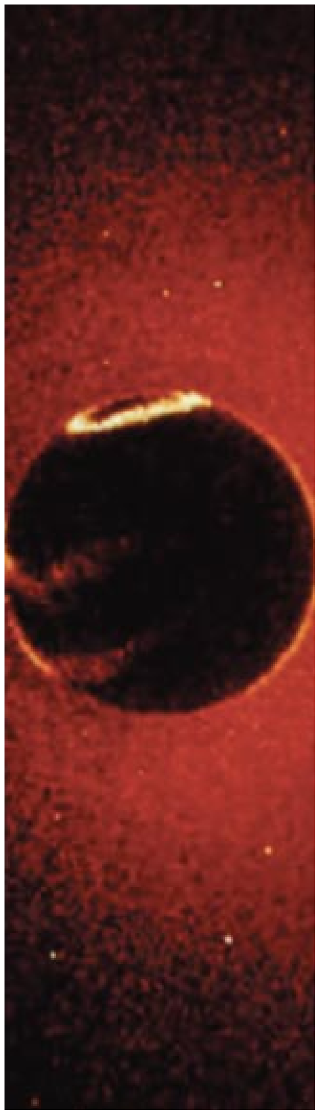
Thermal escape occurs in two ways. In the first, called Jeans escape, after James Jeans, the English astronomer who described it in the early 20th century, air literally evaporates atom by atom, molecule by molecule, off the top of the atmosphere. At lower altitudes, collisions confine particles, but above a certain altitude, known as the exobase, which on Earth is about 500 kilometers above the surface, air is so tenuous that gas particles hardly ever collide. Nothing stops an atom or molecule with sufficient velocity from flying away into space.

As the lightest gas, hydrogen is the one that most easily overcomes a planet's gravity. But first it must reach the exobase, and on Earth that is a slow process. Hydrogen-bearing molecules tend not to rise above the lowest layer of atmosphere: water vapor (H_2O) condenses out and rains back down, and methane (CH_4) is oxidized to form carbon dioxide (CO_2). Some water and methane molecules reach the stratosphere and decompose, releasing hydrogen, which slowly diffuses upward until it reaches the exobase. A small amount clearly makes it out because ultraviolet images reveal a halo of hydrogen atoms surrounding our planet [*see illustration on opposite page*].

The temperature at Earth's exobase oscillates but is typically about 1,000 kelvins, implying that hydrogen atoms have an average speed of five kilometers per second. That is less than Earth's escape velocity at that altitude, 10.8 kilometers per second, but the average conceals a wide range, so some hydrogen atoms still manage to break free of our planet's gravity. This loss of particles from the energetic tail of the speed distribution explains about 10 to 40 percent of Earth's hydrogen loss today. Jeans escape also partly explains why our moon is airless. Gases

GEORGE RETSECK (*illustration*); ALFRED T. KAMAJIAN (*graph*) released from the lunar surface easily evaporate off into space.

A second type of thermal escape is far more dramatic. Whereas Jeans escape occurs when a gas evaporates molecule by molecule, heated air can also flow en masse. The upper atmosphere can absorb ultraviolet sunlight, warm up and expand, pushing air upward. As the air rises, it accelerates smoothly through the speed of sound and then attains the escape velocity. This form of thermal escape is called hydrodynamic escape or, more evocatively, the planetary wind—the latter by analogy to the solar wind, the stream of charged particles blown from the sun into interplanetary space.



LEAKING HYDROGEN ATOMS give off a red glow in this ultraviolet image of Earth's night side, taken by NASA's Dynamic Explorer I satellite in 1982. Oxygen and nitrogen account for the band around the North Pole and the wisps in the tropics.

NASA/UNIVERSITY OF IOWA

Dust in the Wind

Atmospheres rich with hydrogen are the most vulnerable to hydrodynamic escape. As hydrogen flows outward, it can pick up and drag along heavier molecules and atoms with it. Much as the desert wind blows dust across an ocean and sand grains from dune to dune, while leaving cobbles and boulders behind, the hydrogen wind carries off molecules and atoms at a rate that diminishes with their weight. Thus, the present composition of an atmosphere can reveal whether this process has ever occurred.

In fact, astronomers have seen the telltale signs of hydrodynamic escape outside the solar system, on the Jupiter-like planet HD 209458b. Using the Hubble Space Telescope, Alfred Vidal-Madjar of the Paris Astrophysics Institute and his colleagues reported in 2003 that the planet has a puffed-up atmosphere of hydrogen. Subsequent measurements discovered carbon and oxygen in this inflated atmosphere. These atoms are too heavy to escape on their own, so they must have been dragged there by hydrogen. Hydrodynamic loss would also explain why astronomers find no large planets much closer to their stars than HD 209458b is. For planets that orbit within three million kilometers or so of their stars (about half the orbital radius of HD 209458b), hydrodynamic escape strips away the entire atmosphere within a few billion years, leaving behind only a scorched remnant.

This evidence for planetary winds lends credence to ideas put forth in the 1980s about hydrodynamic escape from ancient Venus, Earth and Mars. Three clues suggest this process once operated on these worlds. The first concerns noble gases. Were it not for escape, chemically unreactive gases such as neon or argon would remain in an atmosphere indefinitely. The abundances of their different isotopes would be similar to their original values, which in turn are similar to that of the sun, given their common origin in the solar nebula. Yet the abundances differ.

Second, youthful stars are strong sources of ultraviolet light, and our sun was probably no exception. This radiation could have driven hydrodynamic escape.

Third, the early terrestrial planets may have had hydrogen-rich atmospheres. The hydrogen could have come from chemical reactions of water with iron, from nebular gases or from water molecules broken apart by solar ultraviolet radiation. In those primeval days, asteroids and comets hit more frequently, and whenever they smacked into an ocean, they filled the atmosphere with steam. Over thousands of years the steam condensed and rained back onto the surface, but Venus is close enough to the sun that water vapor may have persisted in the atmosphere, where solar radiation could break it down.

Under such conditions, hydrodynamic escape would readily operate. In the 1980s James F. Kasting, now at Pennsylvania State University, showed that hydrodynamic escape on Venus could have carried away an ocean's worth of hydrogen within a few tens of millions of years [see "How Climate Evolved on the Terrestrial Planets," by James F. Kasting, Owen B. Toon and James B. Pollack; Scientific American, February 1988]. Kasting and one of us (Zahnle) subsequently showed that escaping hydrogen would have dragged along much of the oxygen but left carbon dioxide behind. Without water to mediate the chemical reactions that turn carbon dioxide into carbonate minerals such as limestone, the carbon dioxide built up in the atmosphere and created the hellish Venus we see today.

To a lesser degree, Mars and Earth, too, appear to have suffered hydrodynamic losses. The telltale signature is a deficit of lighter isotopes, which are more easily lost. In the atmospheres of Earth and Mars, the ratio of neon 20 to neon 22 is 25 percent smaller than the solar ratio. On Mars, argon 36 is similarly depleted relative to argon 38. Even the isotopes of xenon—the heaviest gas in Earth's atmosphere apart from pollutants—show the imprint of hydrodynamic escape. If hydrodynamic escape were vigorous enough to sweep up xenon, why did it not sweep up everything else in the atmosphere along with it? To solve this puzzle, we may need to construct a different history for xenon than for the other gases now in the atmosphere.

Hydrodynamic escape may have stripped Titan of much of its air, too. When it descended through Titan's atmosphere in 2005, the European Space Agency's Huygens probe found that the ratio of nitrogen 14 to nitrogen 15 is 70 percent of that on Earth. That is a huge disparity given that the two isotopes differ only slightly in their tendency to escape. If Titan's atmosphere started with the same nitrogen isotopic composition as Earth's, it must have lost a huge amount of nitrogen—several times the substantial amount it currently has—to bring the ratio down to its present value. In short, Titan's atmosphere might once have been even thicker than it is today, which only heightens its mystery.

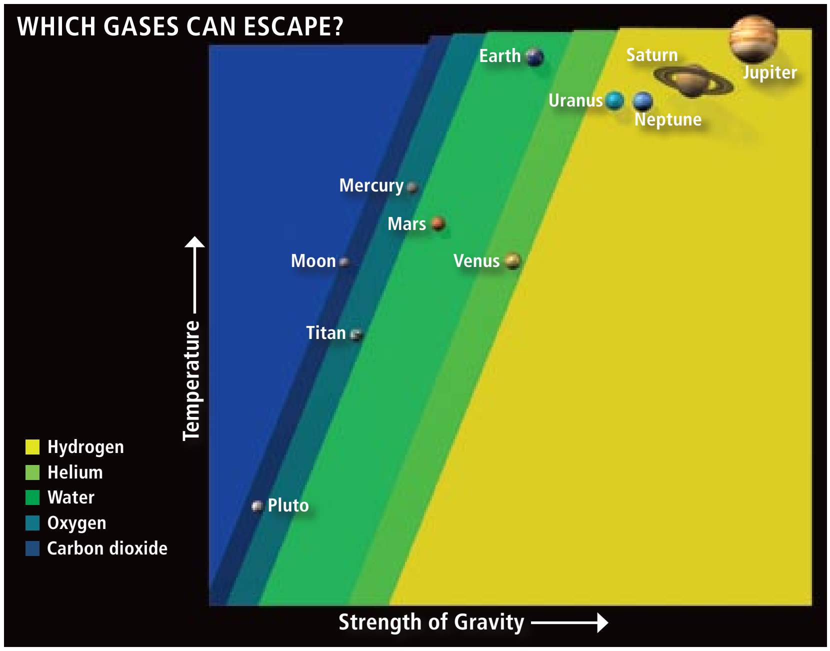
Better Escaping through Chemistry

On some planets, including modern Earth, thermal escape is less important than nonthermal escape. In nonthermal escape, chemical reactions or particle-particle collisions catapult atoms to escape velocity. What nonthermal escape mechanisms have in common is that an atom or molecule reaches a very high velocity as the outcome of a single event that takes place above the exobase, so that bumping into something does not thwart the escapee. Many types of nonthermal escape involve ions. Ordinarily these charged particles are tethered to a planet by its magnetic field, either the global (internally generated) magnetic field—if there is one—or the localized fields induced by the passage of the solar wind. But they find ways to slip out.

In one type of event, known as charge exchange, a fast hydrogen ion collides with a neutral hydrogen atom and captures its electron. The result is a fast neutral atom, which is immune to the magnetic field. This process accounts for 60 to 90 percent of the present loss of hydrogen from Earth and most of the hydrogen loss from Venus.

Another way out exploits a weak spot—dare we say a loophole—in the planet's magnetic trap. Most magnetic field lines loop from one magnetic pole to the other, but the widest field lines are dragged outward by the solar wind and do not loop back; they remain open to interplanetary space. Through this opening, ions can escape. To be sure, the ions must still overcome gravity, and only the lightest ions such as hydrogen and helium make it. The resulting stream of charged particles, called the polar wind (not to be confused with the planetary wind), accounts for 10 to 15 percent of Earth's hydrogen loss and almost its entire helium leak.

In some cases, these light ions can sweep up



LIGHT GASES such as hydrogen are more footloose than heavier ones such as oxygen. Their susceptibility to Jeans escape depends on the temperature at the top of a body's atmosphere or, for airless bodies such as the moon, at its surface (*vertical axis*) and on the strength of its gravity (*horizontal axis*). If a body lies to the right of the line for a gas, it holds on to the gas; to the left, it loses the gas. For example, Mars loses hydrogen and helium, retains oxygen and carbon dioxide, and barely retains water.

heavier ions with them. This process may explain the xenon puzzle: if the polar wind was more vigorous in the past, it could have dragged out xenon ions. One piece of evidence is that krypton does not have the same isotopic pattern as xenon does, even though it is a lighter gas and, all else being equal, ought to be more prone to escape. The difference is that krypton, unlike xenon, resists ionization, so even a strong polar wind would have left it unaffected.

A third nonthermal process known as photochemical escape operates on Mars and possibly on Titan. Oxygen, nitrogen and carbon monoxide molecules drift into the upper atmosphere, where solar radiation ionizes them. When the ionized molecules recombine with electrons or collide with one another, the energy released splits the molecules into atoms with enough speed to escape.

Mars, Titan and Venus lack global magnetic fields, so they are also vulnerable to a fourth nonthermal process known as sputtering. Without a planetary field to shield it, the upper atmosphere of each of these worlds is exposed to the full brunt of the solar wind. The wind picks up ions, which then undergo charge exchange and escape. Mars's atmosphere is enriched in heavy nitrogen and carbon isotopes, suggesting that it

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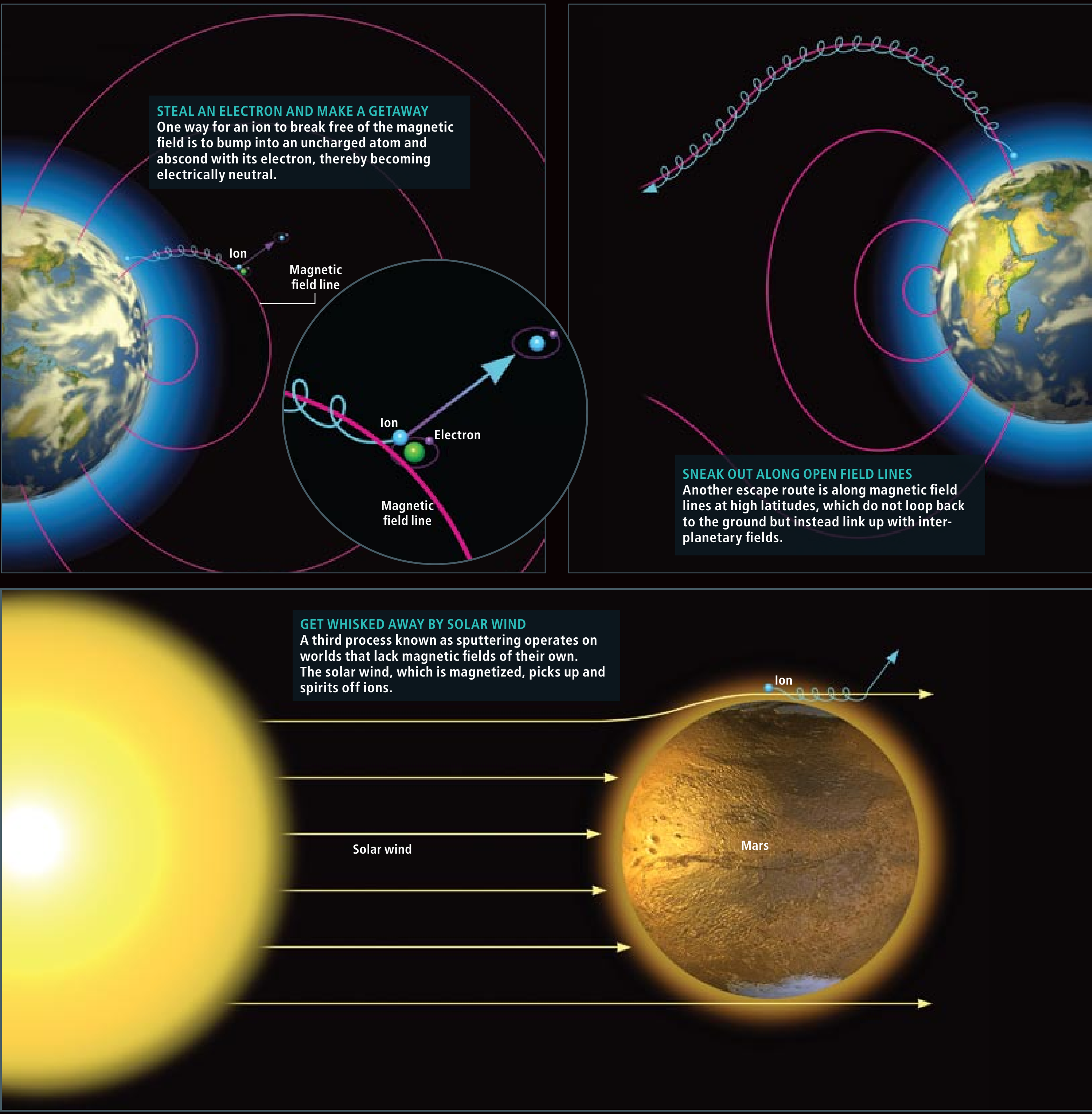
ALFRED T. KAMAJIAN (*graph*); GEORGE RETSECK (*illustration*)

[ESCAPE MECHANISM #2]

The Houdini Particles

The second broad way that air escapes is through charged particle reactions. Electric fields readily accelerate ions to escape velocity. The planet's magnetic field traps them, but they have various tricks to slip out.

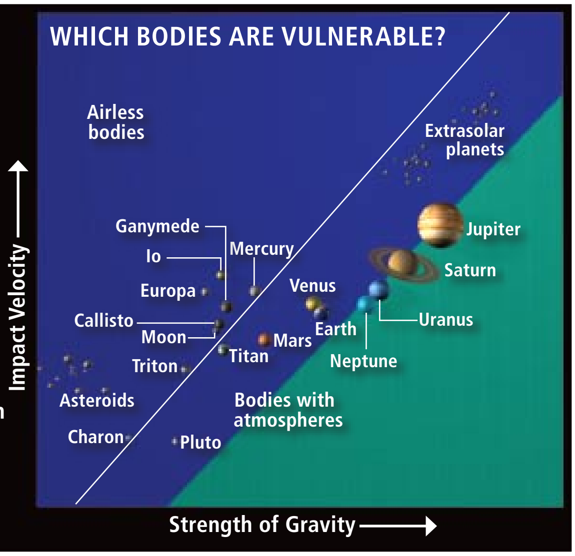


[ESCAPE MECHANISM #3]

AIR BLAST

When a comet or asteroid strikes a planet, it creates an enormous explosion that throws rock, water, dinosaurs and air into space.

IMPACT EROSION is most severe when a body has weak gravity (*horizontal axis*) and when the incoming asteroids or comets smack at high speed (*vertical axis*). Airless bodies tend to lie toward the upper left of the graph, where erosion is worst. (The strength of gravity sets a minimum impact velocity, so the greenish area represents a range of velocities that can never arise in nature.)



GEORGE RETSECK (*illustration*); ALFRED T. KAMAJIAN (*graph*)

has lost as much as 90 percent of an earlier atmosphere. Sputtering and photochemical escape are the most likely culprits. In 2013 NASA plans to launch the Mars Atmosphere and Volatile EvolutioN (MAVEN) mission to measure escaping ions and neutral atoms and reconstruct the planet's atmospheric history.

Inescapable Consequences

Both thermal and nonthermal escape are like tiny trickles compared with the huge splash when comets or asteroids crash into planets. If projectiles are sufficiently big and fast, they vaporize both themselves and a similar mass of the surface. The ensuing hot gas plume can expand faster than the escape velocity and drive off the overlying air. The larger the impact energy, the wider the cone of atmosphere ejected. For the asteroid that killed off the dinosaurs 65 million years ago, the cone was about 80 degrees wide from the vertical and contained a hundred-thousandth of the atmosphere. An even more energetic impact can carry away the entire atmosphere above a plane that is tangent to the planet.

Another factor determining the width of the cone is the atmospheric density. The thinner the air, the greater the fraction of the atmosphere that gets lost. The implication is gloomy: once a vulnerable atmosphere starts wearing away, impact erosion becomes ever easier until the atmosphere vanishes altogether. Unfortunately, Mars spent its youth in a bad neighborhood near the asteroid belt and, being small, was especially susceptible. Given the expected size distribution of impactors early in a solar system's history, the planet should have been stripped of its entire atmosphere in less than 100 million years.

The large moons of Jupiter also live in a dangerous neighborhood—namely, deep in the giant planet's gravitational field, which accelerates incoming asteroids and comets. Impacts would have denuded these moons of any atmospheres they ever had. In contrast, Titan orbits comparatively far from Saturn, where impact velocities are slower and an atmosphere can survive.

In all these ways, escape accounts for much of the diversity of atmospheres, from the lack of air on Callisto and Ganymede to the absence of water on Venus. A more subtle consequence is that escape tends to oxidize planets, because hydrogen is lost more easily than oxygen. Hydrogen escape is the ultimate reason why Mars, Venus and even Earth are red. Most people do not think of Earth as a red planet, but much of the continental crust is red. Soil and vegetation hide this native hue. All three worlds started out the gray-black color of volcanic rock and reddened as the original minerals oxidized to iron oxides (similar to rust). To account for its color, Mars must have lost an ocean of water equivalent to a global layer meters to tens of meters deep.

On Earth, most researchers attribute the accumulation of oxygen 2.4 billion years ago to photosynthetic organisms, but in 2001 we suggested that the escape of hydrogen also played an important role. Microbes break apart water molecules in photosynthesis, and the hydrogen can pass like a baton from organic matter to methane and eventually reach space. The expected amount of hydrogen loss matches the net excess of oxidized material on Earth today.

Escape helps to solve the mystery of why

[WHICH MECHANISMS APPLY WHERE]

A Litany of Losses

The three escape processes operate to different degrees on different planets and at different points in their history.

			THERMAL		NONTHERMAL				IMPACT
BODY	PERIOD	KEY GASES LOST	JEANS ESCAPE	HYDRO-DYNAMIC	CHARGE EXCHANGE	POLAR WIND	PHOTO-CHEMICAL	SPUTTERING	
Earth 	Now	Hydrogen	✓		✓	✓			
		Helium			✓	✓			
	Primordial	Hydrogen, neon		✓					
Venus 	Now	Hydrogen, helium			✓			✓	
	Primordial	Hydrogen, oxygen		✓					
Mars 	Now	Hydrogen	✓						
		Carbon, oxygen, nitrogen, argon					✓	✓	
	Primordial	All gases							✓
		Hydrogen, carbon dioxide		✓					
Jupiter's satellites 	Primordial	All gases		✓					✓
Titan 	Now	Hydrogen	✓					✓	
		Methane, nitrogen		?				✓	✓
	Primordial	Hydrogen, methane, nitrogen		✓					
Pluto 	Now	Hydrogen, methane, nitrogen		?					
HD 209458b	Now	Hydrogen, carbon, oxygen		✓					

Mars has such a thin atmosphere. Scientists have long hypothesized that chemical reactions among water, carbon dioxide and rock turned the original thick atmosphere into carbonate minerals. The carbonates were never recycled back into carbon dioxide gas because Mars, being so small, cooled quickly and its volcanoes stopped erupting. The trouble with this scenario is that spacecraft have so far found only a single small area on Mars with carbonate rock, and this outcrop probably formed in warm subsurface waters. Moreover, the carbonate theory offers no explanation for why Mars has so little nitrogen or noble gases. Escape provides a better answer. The atmosphere did not get locked away as rock; it dissipated into space.

A nagging problem is that impact erosion ought to have removed Mars's atmosphere altogether. What stopped it? One answer is simple chance. Large impacts are inherently rare, and their frequency fell off rapidly about 3.8 billion years ago, so Mars may have been spared the final devastating blow. A large impact of an icy asteroid or comet could have deposited more volatiles than subsequent impacts could remove. Alternatively, remnants of Mars's atmosphere may have survived underground and leaked out after the bombardment had subsided.

Although Earth seems comparatively unscathed by escape, that will change. Today hydrogen escape is limited to a trickle because the principal hydrogen-bearing gas, water vapor, condenses in the lower atmosphere and rains back to the surface. But our sun is slowly brightening at about 10 percent every billion years. That is imperceptibly slow on a human timescale but will be devastating over geologic time. As the sun brightens and our atmosphere warms, the atmosphere will get wetter, and the trickle of hydrogen escape will become a torrent.

This process is expected to become important when the sun is 10 percent brighter—that is, in a billion years—and it will take another billion years or so to desiccate our planet's oceans. Earth will become a desert planet, with at most a shrunken polar cap and only traces of precious liquid. After another two billion years, the sun will beat down on our planet so mercilessly even the polar oases will fail, the last liquid water will evaporate and the greenhouse effect will grow strong enough to melt rock. Earth will have followed Venus into a barren lifelessness. ■

➥ MORE TO EXPLORE

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