The escape of planetary atmospheres

Consider a few examples to appreciate the strange variety of planetary atmospheres. Callisto and Titan, moons of Jupiter and Saturn, respectively, are similar in size and mass. Yet Titan has a nitrogen-rich atmosphere with 13 times more nitrogen above each square meter than the Earth, whereas Callisto is essentially airless. Or compare Earth and Venus. Again we see planets of comparable dimensions, but Venus' predominantly carbon dioxide atmosphere exerts over 90 times the surface pressure of the terrestrial atmosphere and warms the Venusian surface to a dessicating 460°C through its huge greenhouse effect.

What causes such extremes? If we knew, it would help explain why the Earth has an atmosphere and surface suitable for biology while planetary surfaces elsewhere in the Solar System are apparently lifeless. Also, as astronomers discover ever smaller extrasolar planets, knowledge of how atmospheric evolution works will be our essential guide to which planets might be habitable.

On human timescales, there is a tendency to think of an atmosphere as being as immutable as a planet's rocks, but over geological time, gases can leak from the top of the atmosphere and escape to space. Fortunately, for the modern Earth, loss rates are tiny even for the lightest gases: about 3 kilograms per second of hydrogen and 50 grams per second of helium. But in the last few decades, we have begun to appreciate how the very existence of an atmosphere depends as much on escape as supply. In particular, the atmospheres on terrestrial planets and outer planet satellites are like the ruins of medieval castles, remnants of riches that have been subject to histories of plunder and decay. Atmospheres of small planets are more like crude forts, poorly defended and extremely vulnerable. For decades people have pondered how the smallness of Mars might be responsible for an atmosphere only one hundredth as dense as Earth's—but a consideration of escape makes us wonder why Mars has any atmosphere at all. Odd puzzles also exist for larger terrestrial planets. How did Venus steadfastly cling to a thick atmosphere yet thoroughly lose its water?

To escape, atmospheric gases must attain escape velocity, which is the minimum needed to overcome gravity. One way that this can happen is when gases get too hot to hold on to—so-called thermal escape. Escape can also occur through numerous "non-thermal" processes, where individual atoms or molecules get an energy boost from chemical or charged particle reactions. A third, completely different process, is when air is blasted away by asteroid or comet impacts.

ESCAPING WHEN THE HEAT IS ON OR UNDER PRESSURE

Broadly put, a planet has three ways to deal with the energy of sunlight that it absorbs: it can thermally radiate an equal amount of energy to space, it can get hotter, or it can evaporate and shed matter to space. In long-lived objects, the first case of energy balance prevails, and so this is usually what we see. The other possibilities demand that the planet evolve. Comets provide an extreme example of evaporation and shedding, but even a planet the size of the Earth can heat up quickly compared to the pace of stellar evolution if absorption and radiation get out of balance. Atmospheres, which often have very little mass compared to the mass of the planet, can slough off in a cosmic instant.

Our Solar System is littered with airless bodies and we suspect that thermal atmospheric escape is a common culprit.

One way to address this suspicion is to compare the intensity of sunlight to a planet's escape velocity. When these quantities are plotted against each other, planets with atmospheres stand out as those with high escape velocities subject to less intense sunlight (**Fig. 1**). On this basis, we predict that astronomers will not find Neptune-sized planets as hot as many "hot Jupiters" already discovered because of atmospheric instability.

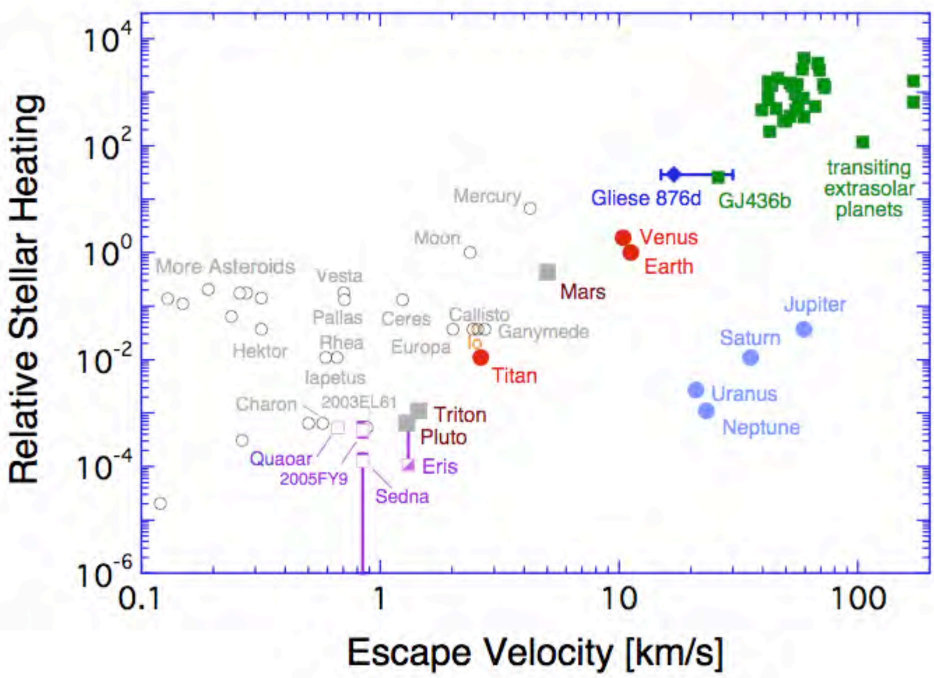


Fig 1: Atmospheres are found where gravity is high and solar heating low. We show this here by plotting heating from the parent star versus escape velocity for solar system bodies and extrasolar planets. The presence or absence of an atmosphere is indicated by filled or open symbols, respectively. The graph demonstrates decreasing atmospheric stability from lower right to upper left. To the lower right of the plot are bodies with substantial atmospheres. Those lying close to a diagonal between upper left and lower right, such as Triton, have thin atmospheres, while those far to the upper left, such as various asteroids, the Moon or Mercury are barren of air.

To describe the theory of thermal atmospheric escape, one starts with the concept that at a high altitude, which is around 500-600 km for Earth, the frequency of collisions between gas particles becomes negligible. Above this "exobase" is the "exosphere", where a planet's atmosphere merges into the vacuum of space. At the exobase, ascending particles are unobstructed, so particles fly away into space if they are moving upwards faster than the escape velocity. Below the exobase, collisions confine the particles.

For gases to escape, they must be carried up through an atmosphere, converted to the form that escapes (often through decomposition into atoms, which are lighter than their parent molecules), and overcome gravity. Usually at least one of these steps is slow and controls the escape rate. For example, the small escape of hydrogen on

Earth today results from limited delivery of hydrogen to the exobase. Most water vapor, which carries the hydrogen, condenses out before reaching the stratosphere, while methane, the other carrier of hydrogen, is stymied in its abundance by oxidation in our oxygen-rich atmosphere. Escape from the exobase is then further throttled by the slow upward diffusion of the small amount of hydrogen that originates in water or methane in the stratosphere.

We know that terrestrial hydrogen reaches space because ultraviolet images reveal a halo of hydrogen atoms surrounding the Earth (**Fig. 2**). Some of these atoms are escaping while the rest are trapped. The temperature at Earth's exobase is typically around 1000 K, although it varies as the Sun's ultraviolet output cycles up and down every 11 years or so. At 1000 K, hydrogen atoms have an average speed of 5 km/sec, which is below Earth's escape velocity of 10.8 km/sec at the exobase. Yet hydrogen atoms still manage to escape because many move faster than average. This loss of particles from the energetic tail of the speed distribution is called "Jeans' escape" after James Jeans (from the University of Cambridge), who described it mathematically in the early twentieth century (**Fig. 3**). However, Jeans' escape explains only a fraction of hydrogen loss from various planets: about 30% of the 93,000 tonnes of terrestrial hydrogen that escape each year, and less than 0.01% of the hydrogen that escapes from Venus. Only about one in a million helium atoms is lost from Earth via Jeans' escape. Similarly, Jeans' escape is negligible for the present-day loss of heavy atoms such as nitrogen and carbon from Mars or Titan.

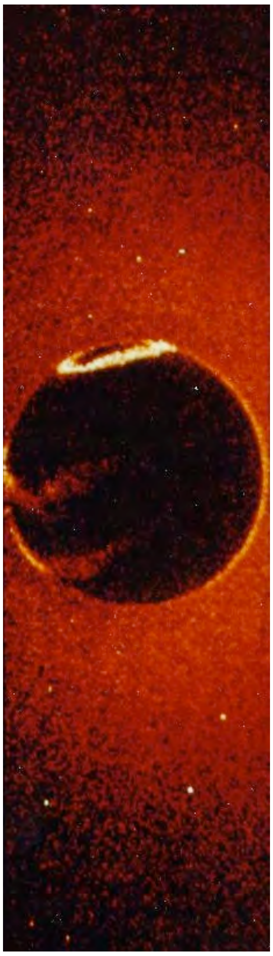


Fig. 2: An ultraviolet image of Earth's dark hemisphere with the Sun behind it, taken from NASA's Dynamic Explorer I spacecraft at 19,700 km altitude above 13° N latitude, on February 16, 1982. The extended red glow around the planet comes from hydrogen atoms in the exosphere. A northern auroral oval and equatorial glow are due to emission from atomic oxygen and molecular nitrogen. Isolated points are stars that are bright in the ultraviolet.
(Courtesy of NASA).

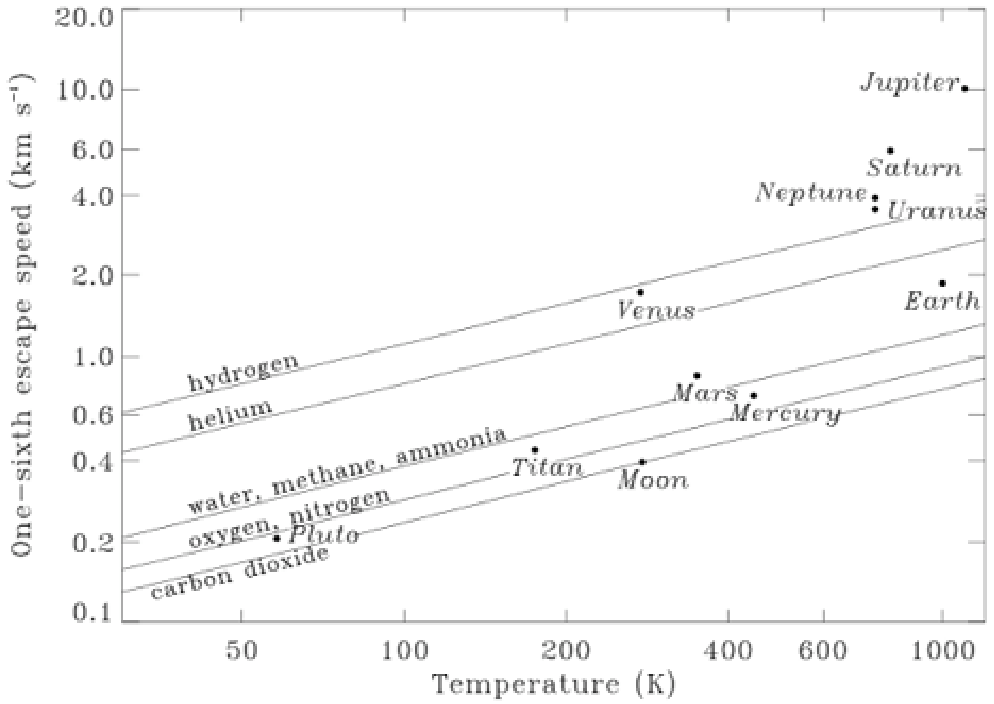


Fig. 3: This graph shows gases that are prone to undergo Jeans' escape on the basis of a 'rule of thumb' where Jeans' escape is considered important if the mean thermal velocity of a gas at the exobase exceeds about a sixth of a planet's escape speed. The temperature plotted for each celestial body corresponds to the average exobase temperature for objects with substantial atmospheres. For the Moon and Mercury, the average surface temperature is plotted. The sloping lines correspond to typical speeds of various gas molecules at the given temperature. For example, the graph shows that hydrogen and helium will easily undergo Jeans' escape on Mars because the lines for these gases lie above the one-sixth escape speed marked by the dot for Mars, whereas water, oxygen, nitrogen and carbon dioxide will not undergo Jean's escape because the lines for these gases lie below the threshold for Mars. Similarly, we see that hydrogen will not escape from the giant planets.

A second type of thermal escape is far more dramatic than Jeans' mechanism. Jeans' escape applies when a gas evaporates molecule by molecule from an exobase. But if conditions favor faster escape, the air flows into the vacuum of space, pushed along by pressure from below. This can occur if the bulk gas in the upper atmosphere is a good absorber of ultraviolet light and the heated air flows en masse. Unlike Jeans' case, the bulk atmosphere is no longer static. The atmosphere flows, accelerates smoothly through the sound speed, and then attains the escape speed and higher. This form of thermal escape is called "hydrodynamic escape" or the "planetary wind," the latter by analogy to the solar wind, the thermal wind of charged particles blown from the Sun into interstellar space.

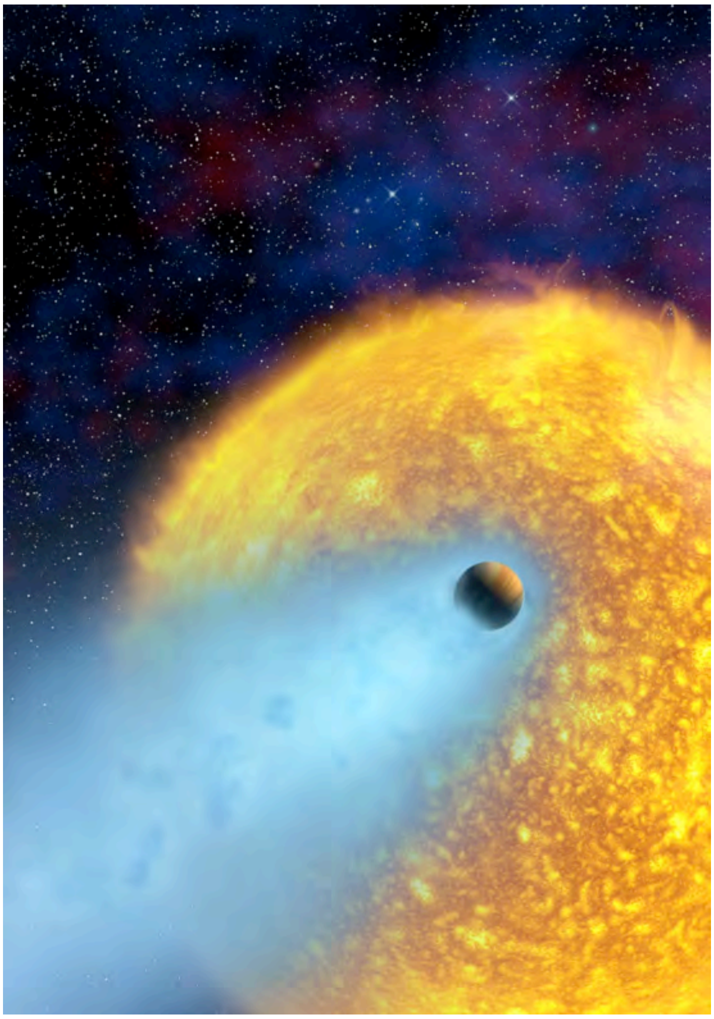


Fig. 4: Artist's impression of the hydrodynamic escape of the atmosphere of the scorched giant planet HD 209458b in its close orbit around its yellow Sun-like star. (Courtesy of ESA/NASA).

As the lightest gas, hydrogen is the one that most easily overcomes a planet's gravity, so atmospheres rich with hydrogen are the most prone to hydrodynamic escape. During hydrodynamic escape, hydrogen can drag along heavier molecules and atoms. A loose analogy is to wind-blown dust: without the wind the dust goes nowhere, but a strong wind can lift the dust. Another point of analogy is that the hydrogen wind preferentially carries off molecules and atoms of low mass, the lighter the better, much as the desert wind can blow dust across an ocean and sand grains from dune to dune, while leaving cobbles and boulders behind. This analogy helps us understand that during hydrodynamic escape of hydrogen, atoms heavier than hydrogen will be dragged upwards at a rate depending upon a competition with gravity. For isotopes (atoms of the same chemical element with different masses), ancient episodes of hydrodynamic escape will leave behind telltale traces by removing lighter isotopes preferentially.

Remarkably, hydrodynamic escape has recently been observed outside the Solar System. A planetary wind appears to blow from the Jupiter-like planet HD 209458b some 150 light years away in the constellation of Pegasus (**Fig.4**). This planet transits in front of a Sun-like star (HD 209458) during its orbit at a distance nine times closer than Mercury is to the Sun. HD 209458b has two-thirds the mass of Jupiter and a diameter of 1.3 times. Using the Hubble Space Telescope's Imaging Spectrograph, Alfred Vidal-Madjar (from the Institut d'Astrophysique de Paris) and colleagues reported in 2003 that a puffed-up atmosphere of hydrogen around HD 209458b extended beyond the planet's gravitational influence, based on measurements of ultraviolet light. Carbon and oxygen were subsequently discovered in the inflated atmosphere, serving as a ‘smoking gun’ for hydrodynamic escape because atoms this heavy would need to have been dragged along by hydrogen. Fast hydrodynamic loss may explain why “hot Jupiter” planets are not found really close to their parent stars. For orbits less than about 3 million kilometers around a Sun-like star, hydrodynamic escape could remove the atmosphere of a Jupiter-like planet within a few billion years, leaving behind only a scorched remnant of its dense core.

The direct observation of a planetary wind lends credence to ideas put forth in the 1980s about hydrodynamic escape in the ancient atmospheres of Venus, Earth and Mars. Three ideas still motivate ancient hydrodynamic escape. The first concerns noble gases. Without escape, chemically unreactive gases, such as neon or argon, should remain indefinitely in atmospheres and the abundances of their different isotopes ought to be similar to the Sun’s, given a common origin from the solar nebula. But the abundances differ. The second factor is that the youthful Sun provided much more intense ultraviolet light to drive hydrodynamic escape. Ultraviolet emission depends on the strength of the Sun’s magnetic field, which modulates the upward transmission of convective energy from depth into the heat that drives emission in the Sun’s chromosphere. In turn, the magnetic field is generated by the Sun’s spin. The young Sun rotated much faster than present because the solar wind has continuously removed angular momentum. Third, the early terrestrial planets may have had more hydrogen-rich atmospheres for some tens to hundreds of millions of years after they formed. Chemical reactions of water with iron likely generated hydrogen as these planets partitioned into core, mantle and crust. Later, steam generated by giant impacts into oceans could have also supplied hydrogen.

Indeed, on early Earth, steam atmospheres probably formed intermittently due to ocean-vaporizing impacts from a few asteroids that were larger than about 500 km across. Such bodies roamed the inner Solar System prior to about four billion years ago—an inference drawn from the large, ancient impact craters seen on the Moon. Steam atmospheres evidently condensed back into an ocean on Earth. On Venus though, which is closer to the Sun, atmospheric water vapor may have persisted instead of collapsing into swelteringly hot oceans. Either way, the consequences for Venus were a searing greenhouse effect from so much water vapor. Water vapor (H_2O) itself is not especially prone to escape but its ultraviolet decomposition at high altitude produces hydrogen and oxygen. In the 1980s, James Kasting (now at Penn State University) showed that an amount of hydrogen comparable to that in Earth’s ocean could have escaped hydrodynamically from early Venus in less than a few hundred million years. One of us [Kevin Zahnle], together with Kasting, subsequently showed that such escape would also have dragged along much of the oxygen. Meanwhile, heavier carbon dioxide would have remained behind. Without water to mediate the chemistry that turns carbon dioxide into carbonate minerals, Venus is left with all its carbon dioxide in its atmosphere rather than predominantly in limestone, as on the Earth. However, a hellish fate lies in store for the future Earth (See Box).

Noble gases provide our best quantitative measure of past hydrodynamic losses. If noble gases escape, the telltale signature is a lack of lighter isotopes that are more easily lost. In the Martian and terrestrial atmospheres, the ratio of neon-20 to neon-22 isotopes is 25 percent smaller than the original solar ratio, consistent with preferential loss of neon-20 during hydrodynamic escape. Indeed, escape may also partially explain the paucity of neon relative to heavier argon. The neon-to-argon ratio on Venus, Earth and Mars is 1 percent of the original solar nebula's. Argon isotopes have also been strongly affected on Mars. The ratio of argon-36 to argon-38 in the atmosphere is about 3.9 compared to 5.3 in the Sun. Argon's loss implies that other gases also escaped because carbon dioxide is similar in mass to argon while molecular nitrogen is lighter. The most surprising evidence for hydrodynamic escape was described in 1987 by Donald Hunten (Univ. of Arizona), Robert Pepin (Univ of Minnesota), and James Walker (Univ of Michigan): the strong mass fractionation in the nine isotopes of terrestrial xenon is exactly what hydrodynamic escape predicts. The puzzling part is that xenon is the heaviest gas likely to be found in an abiotic atmosphere. If hydrodynamic escape were vigorous enough to sweep up xenon, it should have swept away everything else in the atmosphere too.

BOX: ESCAPE AND THE END OF LIFE ON EARTH

Our Sun is slowly brightening at a current rate of about 10% per billion years, but this rate is accelerating and the Sun is destined to become a red giant some 7½ billion years from now. However, long before the Sun reaches that limit, hydrogen escape will have dessicated our planet. Today hydrogen escape is limited to a trickle by the diffusion of H-bearing gases, principally water (H_2O), through the stratosphere. Stratospheric water vapor is in turn controlled by the condensation of water vapor at the top of the equatorial troposphere, where temperatures are lowest. This makes the stratosphere dry and escape slow. As James Kasting (then of the NASA Ames Research Center) pointed out, as the Sun brightens and the top of the troposphere gets warmer, the stratosphere gets wetter and the trickle of hydrogen escape becomes a torrent. This is expected to become important when the Sun is 10% brighter (i.e., in a billion years), and it will take another billion years or so for most of the hydrogen in our oceans to escape. Earth will then have been transformed into a desert planet, with liquid water present but precious. Eventually, after another two billion years, the Sun will be bright enough that all the remaining water evaporates and the greenhouse effect grows strong enough to melt rock. At this point, some 4 billion years from now, Earth will have followed Venus into a barren and lifeless state.

Hydrodynamic escape may be occurring today in Pluto's atmosphere and may be relevant for Titan. In Pluto's atmosphere, the absorption of ultraviolet sunlight by methane and nitrogen could be driving hydrodynamic loss. Measurements by NASA's New Horizons mission, which was launched in 2006 and flies by Pluto in 2015, could give us a glimpse into what is really happening on this remote body. When it descended through Titan's atmosphere in 2005, the European Space Agency/NASA Huygens probe found that the ratio of nitrogen-15 to nitrogen-14 isotopes is fifty percent larger than in Earth's atmosphere and more than twice as heavy as nitrogen measured in Jupiter's atmosphere in 1995 by NASA's Galileo probe. The apparent loss of light nitrogen implies the escape of several times the amount of nitrogen currently in Titan's atmosphere. Possibly, hydrodynamic escape of hydrogen on early Titan dragged along nitrogen with preferential loss of its lighter isotope.

ESCAPING WHEN THE CHEMISTRY IS RIGHT

Let us return to the problem of why Jeans' escape does not account for present-day atmospheric loss from Earth, Venus, Mars and Titan. The answer concerns the plethora of "non-thermal escape" processes, whereby atoms attain escape velocity from chemical or ionic reactions.

An important process for hydrogen loss is "charge exchange", which probably accounts for about 40 percent of the present escape of hydrogen from Earth and most of the hydrogen escape from Venus. Solar radiation creates electrons and positively charged ions in upper atmospheres by tearing electrons off atoms or molecules. Subsequently, charge attraction and repulsion in collisions accelerates ions. On Earth, the magnetic field traps ions, but a fast hydrogen ion can collide with a neutral hydrogen atom and capture its electron. In this exchange of charge, fast ions turn into escaping neutral atoms (**Fig. 5**).

On Earth, another significant non-thermal process is the "polar wind". This wind accounts for an estimated 15% of hydrogen escape and almost the entire loss of terrestrial helium. Escape of the latter balances the rate that helium leaks out of rocks mostly as a byproduct of radioactive decay. The polar wind arises because, near the magnetic poles, open magnetic field lines do not loop around and re-enter the Earth but are dragged outward by the solar wind and remain open to interplanetary space. Closed field lines trap ions but open ones allow light ions to escape. A mechanism exists to produce such upward acceleration. When atoms and molecules are ionized in the upper atmosphere by ultraviolet radiation and X-rays, negatively charged electrons, which are very light, float above the heavier, positively charged ions. The dominant positive ion in the region where most of atomic ion production occurs is O^+, which is too heavy to escape, and so tethers the electrons with an electric field. While the oxygen remains suspended, the electric field can accelerate lighter ions, such as hydrogen and helium out to space. A more vigorous past polar wind may provide an alternative xenon story. Xenon is more easily ionized than hydrogen so xenon ions could be dragged by hydrogen ions in a polar wind. Krypton, which is a lighter noble gas than xenon, resists ionization and has no corresponding pattern of isotopes, consistent with the polar wind loss of xenon.

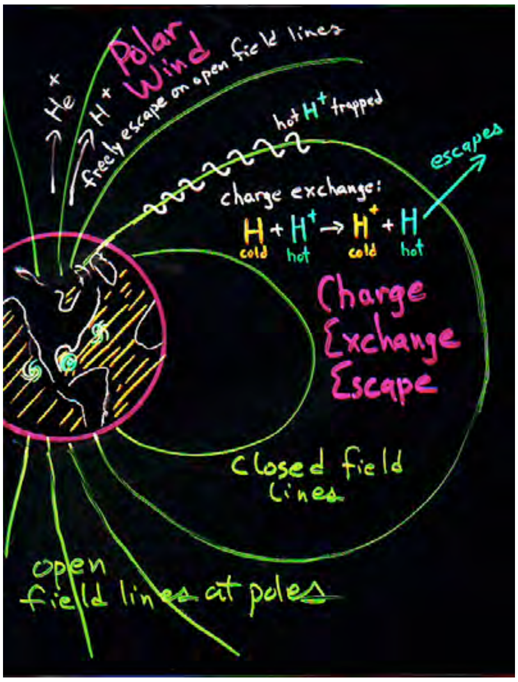
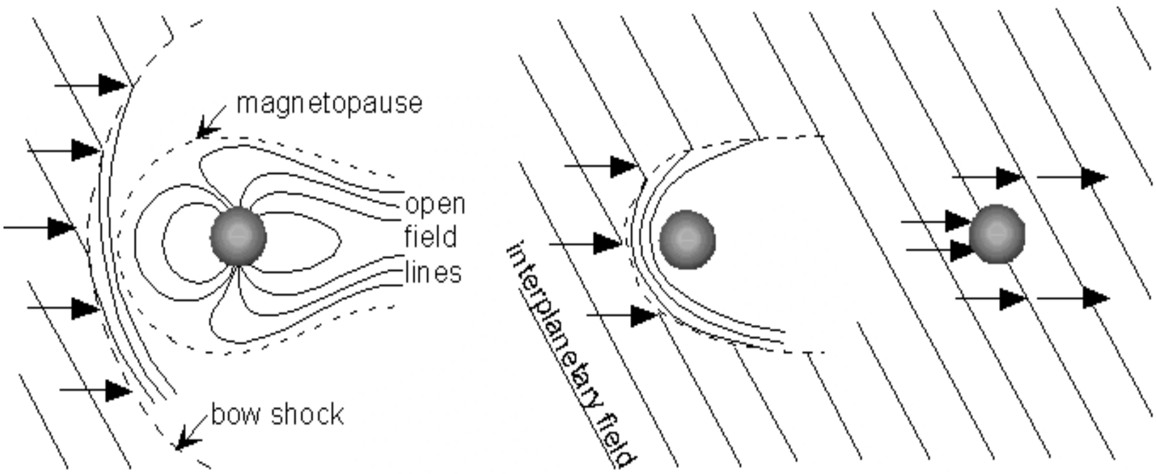


Fig. 5: So-called "non-thermal escape" processes for the Earth

Only hydrogen and helium escape appreciably from Earth today, but on Mars oxygen, nitrogen, and carbon also escape. These heavy atoms escape via non-thermal mechanisms from the Martian exobase at around 230 km altitude. In so-called photochemical escape, nitrogen, oxygen and carbon monoxide molecules are ionized in the upper atmosphere by ultraviolet light. When the ionized molecules and electrons recombine or collide, the energy released splits the molecules into atoms with enough speed to escape. Alternatively, direct ultraviolet decomposition of molecules by ultraviolet light may produce fast enough atoms or ions. Above 120 km altitude on Mars, gases separate diffusively according to mass so that heavier isotopes decrease in abundance with altitude more rapidly. Consequently, lighter isotopes are removed more easily from the exobase. Similar photochemical escape occurs on Titan. Measurements from NASA's Cassini spacecraft indicate that Titan loses hydrogen at a rate of tens of kilograms per second, which is a few times larger than the conventional Jeans' escape rate and might be explained by a skewed velocity distribution. Currently, Titan's nitrogen and carbon escape rates are controversial and under study from Cassini scientists.

Photochemical escape on Mars and Titan is augmented by "sputtering", a non-thermal process that is effective on small planets without magnetic fields. A magnetic field deflects the solar wind at a large distance (**Fig. 6**). But on planets without magnetic fields, ions in the upper atmosphere are picked up by magnetic fields generated by the close flow of the solar wind. The high-speed ions undergo charge exchange and become fast neutral atoms. Following collisions, fast upward-directed particles escape. Mars has had no global magnetic field since about 4 billion years ago, given the lack of remnant magnetism in the ancient 2,300 km-diameter Hellas impact basin, so sputtering has been effective since then. Similar sputtering contributes to Titan's present-day non-thermal loss of carbon and nitrogen, depending on whether Titan is within Saturn's magnetosphere or exposed to the solar wind. On Mars, the enrichment of heavy isotopes of nitrogen and carbon suggests a 50-90% loss of the atmosphere since about 4 billion years ago, both from sputtering and photochemical escape. Sputtering by ions trapped in the fast rotating jovian magnetosphere may also maintain the vacuums on Jupiter's Galilean satellites.



(a) (b) (c)

Fig. 6: Interaction of the solar wind with different planets. (a) A planet that has a significant magnetic field, such as Earth. The magnetopause is a boundary between the planet's field and the solar wind. Within the magnetopause, the planet's magnetic field dominates. Further away, solar wind particles slow down abruptly at a bow shock, like one formed around a supersonic bullet or airplane, where some of the energy of motion is converted to heat. Open field lines allow ions to escape from the poles if they exceed the escape velocity. (b) Interaction of the solar wind with a planet without a significant magnetic field but with an atmosphere, such as present-day Mars. A bow shock still forms due to an induced magnetic field formed within ions in the atmosphere, but it is much closer to the planet. Solar wind particles are slowed down but now they can erode the atmosphere. (c) The solar wind collides directly with a body that has low electrical conductivity, no atmosphere, and no magnetic field, such as the Moon.

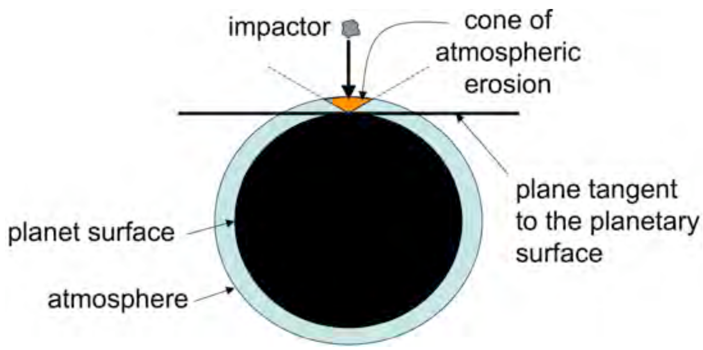


Fig. 7: In impact erosion of a planetary atmosphere, greater energy of impact leads to a wider cone of atmospheric ablation (orange zone) until the entire atmosphere above a plane tangent to the planet is removed.

ESCAPING WITH AN IMPACT

Jeans' and non-thermal escape are like tiny trickles compared to the huge splash when comets or asteroids crash into rocky planets. Jay Melosh (of the University of Arizona), noted that if projectiles are sufficiently big and fast, they vaporize, along with a similar mass of the surface. The ensuing hot gas plume can expand faster than the escape velocity and drive off the overlying air. On Mars, the threshold impact speed for a hot plume is around 14 km/sec for comets and 11 km/sec for asteroids, which is reached by many typical impacts. The larger the impact energy, the wider the cone of atmosphere ejected. For an impactor on the Earth comparable in size and energy to the asteroid that killed off the dinosaurs sixty-five million years ago, the cone's size is theoretically about 77 degrees wide from the vertical, containing some 1/100,000th of the Earth's atmospheric mass. Eventually, if the impact is energetic enough it can carry away the entire atmosphere above a plane that is tangent to the planet (**Fig. 7**). The required impactor mass in this case is roughly equal to the mass of atmosphere ejected. Consequently, thinner atmospheres are more easily eroded. Because smaller impactors are exponentially more numerous, the implication is gloomy: once a vulnerable atmosphere starts wearing away, impact erosion becomes ever easier until the atmosphere vanishes. Unfortunately, Mars spent its youth in a bad neighborhood and, being small, was susceptible to this tragedy. Given the expected size distribution of impactors during the first 500 million years of Solar System history, Mars should have been stripped of its entire atmosphere in less than 100 million years, begging the question of why Mars now has any atmosphere at all.

In the Solar System, impact speeds depend on location. Callisto and Ganymede revolve deep in the gravitational field of Jupiter, so that impactors are fast (**Fig. 8**). Consequently, these moons were subject to being denuded of thick atmospheres, if they ever had them. Titan revolves more slowly about Saturn, so that impact velocities are slower and an atmosphere can be retained and even grow from gases released by cometary impacts.

INESCAPABLE CONSEQUENCES

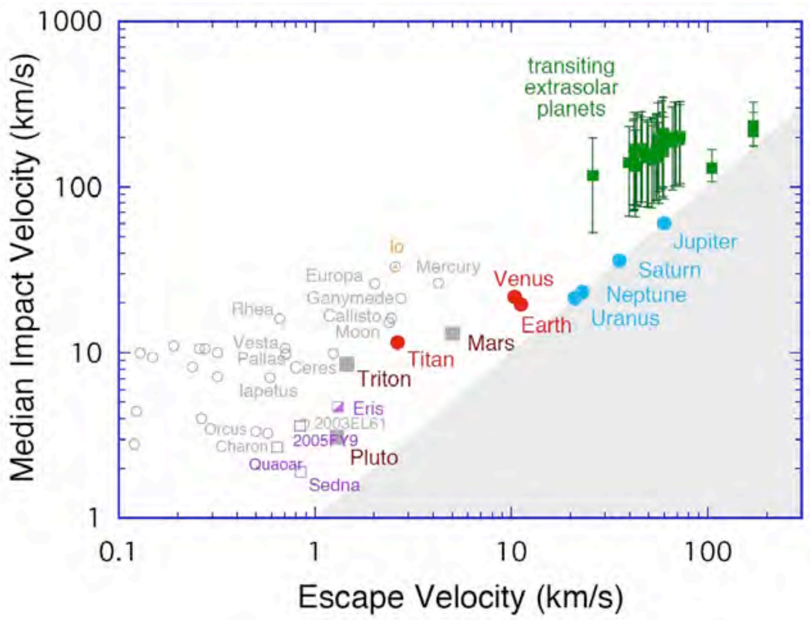


Fig. 8: Atmospheres occur where gravity is high and impact velocities are low. This plot shows the median impact velocity (which should be proportional to the highest velocities of the impact ejecta) on a celestial body versus the body's escape velocity. The shaded area is an unphysical zone where the impact velocity is less than the escape velocity. The presence or absence of an atmosphere is indicated by filled or open symbols, respectively. Encounter velocities in our Solar System are estimated for the appropriate group of stray bodies (asteroids for inner planets and ecliptic comets for Jovian planets and satellites). Error bars for transiting exoplanets reflect the range of plausible impact velocities that such planets might experience in their current orbits. The plot reveals a decreasing trend of atmospheric stability from lower right to upper left. The further to the upper left, the more bodies will suffer atmospheric impact erosion.

Atmospheric escape has consequences. We have mentioned the lack of air on Callisto and Ganymede, and 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 and Venus are red, and probably also why much of Earth's continental crust is red. Mars started out the gray-black color of volcanic rock. Its redness arises from oxidation of volcanic minerals to iron oxides, which requires that an amount of hydrogen from water has been lost to space to balance the oxygen left behind. Loss of hydrogen from water equivalent to a global layer meters to tens of meters deep accounts for Mars's observed oxidation. Under Venus's veil of clouds, there is also a red surface similarly attributable to hydrogen escape. In 2001, we suggested that Earth's accumulation of photosynthetic oxygen 2.4 billion years ago (when Earth's continental surface first turned red) was accelerated by the escape of hydrogen from an atmosphere rich in biogenic methane that preceded oxygenation. In Earth's case, we proposed that water molecules were broken microbially and the hydrogen passed like a baton from organic matter to methane, before reaching space. Cumulative hydrogen loss is consistent with a net excess of oxidized material now present in the overall inventory of Earth's crust, ocean and atmosphere.

Of the major planets, Mars has the atmosphere that we think is most severely sculpted by escape. Mars is one-ninth the mass of Earth, a difference that has long been suspected as somehow responsible for the thin atmosphere. A popular suggestion has been that reactions between water, carbon dioxide, and rock turned Mars's original thick atmosphere into carbonate rock. In this story, Mars, being small, cooled quickly, and volcanoes long ago ceased to decompose the carbonates back into carbon dioxide gas. But no carbonate outcrops have been found. Moreover, the theory also has no explanation for why Mars has so little nitrogen or noble gases.

While escape provides the best explanation of Mars's thin atmosphere, a nagging problem is that impact erosion ought to have removed the atmosphere altogether. One explanation is chance. The size distribution of impacts is such that, in any snapshot in time, most of the mass resides in one or two largest objects. Meanwhile, the frequency of impacts falls off rapidly with time after about 3.8 billion years ago, such that a particularly big impact is bigger than all subsequent ones. By chance, a large impact (for example, an icy asteroid or comet) could deposit more volatiles than all subsequent impacts can remove. Alternatively, remnants of Mars's atmosphere may have survived underground when atmospheric gases between subsurface grains were trapped by ice or salt sealing the pores. An underground atmosphere is relatively safe from impact predation and the stored gases could have leaked out after the impacts had subsided.

Our other neighbor, Venus, appears to have been volcanically resurfaced some 500-1000 million years ago, so that her ancient secrets will not be divulged easily. But we predict that one day astronomers will observe an early Venus-like planet shedding its water as the planet sweats under the intense ultraviolet light from its young parent star. When this and other exoplanet atmospheres are known, a generalized theory of atmospheric evolution for planets large and small should emerge. From what we know so far, it seems inescapable that escape will play a prominent role.

SUMMARY TABLE: Planets and the principal mechanisms by which they currently lose atmospheric gases. Also shown are the dominant loss mechanisms for early planetary atmospheres, which we take as before about 4 billion years ago.

PLANET	KEY GASES LOST	DOMINANT MECHANISMS
Earth	Hydrogen	Charge exchange, Jeans, polar wind
	Helium	Polar wind, charge exchange
Early Earth	Hydrogen and moderately light gases, including neon	Hydrodynamic escape and drag
Venus	Hydrogen, helium	Charge exchange, sputtering
Early Venus	Hydrogen and moderately light gases, including oxygen	Hydrodynamic escape and drag
Mars	Hydrogen	Jeans
	Carbon, oxygen, nitrogen, argon	Sputtering, photochemical
Early Mars	All gases	Impact erosion
	Hydrogen and many heavier gases, including carbon dioxide	Hydrodynamic escape and drag
Early Callisto, Ganymede, and Europa	All gases	Impact erosion, hydrodynamic escape and drag
Titan	Hydrogen	Jeans, photochemical
	Methane, Nitrogen	Photochemical, (hydrodynamic flow?), sputtering
Early Titan	Hydrogen, methane, nitrogen	Hydrodynamic escape and drag
Pluto	Hydrogen, methane, nitrogen	Hydrodynamic escape?
HD 209458b and similar 'Hot Jupiters'	Hydrogen and light gases, including carbon and oxygen atoms	Hydrodynamic escape and drag

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