Comparative planetology: History of water in the inner solar system

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In the early solar system, distribution of volatiles such as water, carbon dioxide, methane, and ammonia was determined by the radial temperature gradient produced by solar radiation, resulting in the ultimate formation of small, volatile-poor terrestrial-type planets in the inner solar system and massive, volatile-rich gas giants in the outer solar system. Any volatiles present above the surfaces of the terrestrial planets (Mercury, Venus, Earth, and Mars) are the result of outgassing from their interiors. During more than five decades of studying the planets of the inner solar system by increasingly more sophisticated spacecraft, much has been learned about the past and present inventories of volatiles at various planets and about the physical processes responsible for volatile losses. We now know from observations at Venus and Mars that both planets had oceans for extended periods of up to perhaps a billion years. This paper reviews what has been learned from spacecraft missions about the initial volatile inventories (especially water) at Venus and Mars in comparison with the Earth, and delineates the processes discovered to be responsible for volatile losses at these planets. In particular, planetary magnetic fields are shown to be important in preventing volatile loss by shielding planetary exospheres from the solar wind.

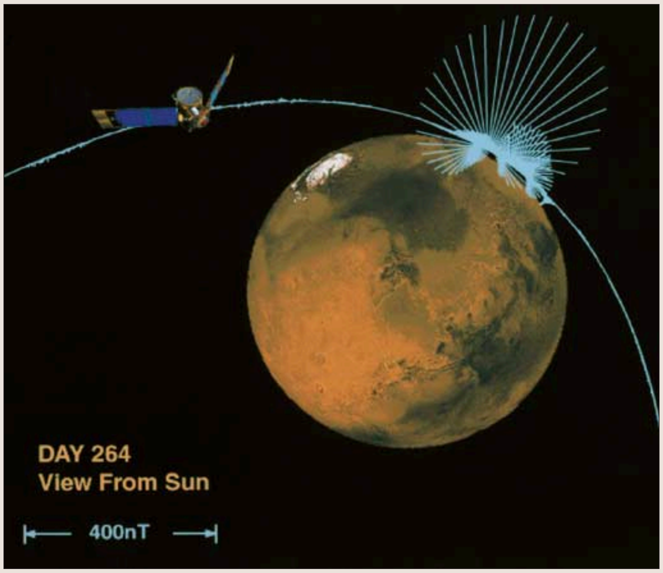

Figure 1. *View of Mars from direction of the Sun on 21 September 1998 showing magnetic field vectors (light blue) along the orbit of the Mars Global Surveyor spacecraft. The distinctive fan-shaped field vector patterns shown at periapse are caused by two magnetic dipoles located just beneath the Martian crust in ancient heavily-cratered terrain in the vicinity of Cassini Crater. These dipoles show remnant magnetic crustal fields frozen into lava flows which occurred over 3.5 billion years ago during the time when Mars had an active planetary dynamo magnetic field. Clearly visible in this image of Mars are the Tharsis bulge with Olympus Mons and the three large Tharsis Montes volcanoes (light red area at lower left), the extensive Valles Marineris canyon (at lower right), created by enormous water floods billions of years ago on Mars, and the north polar ice cap (at upper left), made up of a mixture of carbon dioxide and water ice.*

Background. We believe that life on Earth and elsewhere depends upon the availability of liquid water together with other simple volatile compounds such as methane, carbon dioxide, and ammonia. Indeed, early "Mars jar" experiments which circulated these compounds in a closed system with an energy source (electric spark) quickly produced all the amino acids upon which Earth-based life depends. However, in any solar system, the inner zone where solar radiation produces temperatures that are high enough for water to exist as a liquid is, in fact, the region in which water and the other volatile compounds are most scarce. This scarcity of volatiles in the inner solar system is a consequence of the radial temperature gradient set up early in the history of the solar system by solar radiation. Solar systems form by gravitational collapse of giant gas clouds within a galaxy, with the most rapidly collapsing center forming the star (or multiple stars in some cases) and the outer regions of the cloud forming a flattened protoplanetary disc under the combined effects of gravity from the central star and centrifugal force due to cloud rotation. Within the protoplanetary disc, accretion processes cause gases to condense onto dust grains and coated grains to stick together, producing small marble-size bodies which further coalesce into large bodies, eventually producing protoplanetessimal bodies several hundred kilometers in radius. All bodies, large or small, absorb solar radiation and then re-emit radiation, establishing a radiative equilibrium temperature gradient throughout the forming solar system. In the inner part of the solar system, the radiative equilibrium temperature is above the vaporization or sublimation temperatures of water, carbon dioxide, methane, and ammonia ices, causing these compounds to evaporate off the surfaces and outgas from the interiors of small bodies containing them.

Subsequent photoionization and Lorentz-force pickup by the outward-flowing solar wind then sweeps these volatiles outward from the inner solar system. The early sun drove a solar wind perhaps one million times more intense than the present solar wind. In the outer solar system, these volatiles were swept up by the planets orbiting in the regions where temperatures were low enough to maintain volatiles as ices. Because the total mass of volatiles in the protoplanetary disc vastly exceeded the mass of rocky or metallic materials, the result was the formation of small, rocky terrestrial planets with very little volatiles in the inner solar system and massive, giant planets containing most of the solar system's volatiles in the outer solar system. Today, this process may be seen when small, icy bodies from the outer solar system approach the sun and become visible as comets.

Given these facts, that water and other volatiles are not likely to be abundant in the inner solar system where temperatures are high enough for liquid water to exist, several obvious questions emerge. First, what processes allowed some volatiles to be retained by planets in the inner solar system and what initial quantities were retained? Second, what processes, if any, added to volatile inventories of planets in the inner solar system? And third, what processes either inhibit or enhance loss of volatiles from planets? The following sections will address these questions with answers provided by instrumentation carried by spacecraft orbiting Venus and Mars.

Initial volatile inventories in the inner solar system. In the early solar system, planetary formation and planetary destruction occurred simultaneously with millions of small planetessimals merging to form larger bodies and impacting larger bodies to destroy them. This period, called the "giant impact period," lasted perhaps one billion years until most of the impactors had been incorporated into larger planetary bodies or had been either ejected from the solar system or thrown into the sun by gravitational interactions with large planets. The terrestrial planets, with convective interiors and molten surfaces, had formed from material largely depleted in volatiles, and with their low surface gravities and high surface temperatures, they lost whatever gases reached their surfaces from their interiors. Only after their surfaces cooled sufficiently could they retain an atmosphere, and the atmospheres they retained were composed entirely of gases outgassed from their interiors, volatiles which had been incorporated in minerals in their interiors. Thus, volatiles such as water and carbon dioxide in the atmospheres of Venus, Earth, and Mars originated from hydrates and carbonates in their interiors. Of these three planets, it appears that only the Earth continues to outgas through volcanism, and the Earth also resupplies water, carbon dioxide, and other gases to the interior through plate tectonics and subduction. Although we often refer to the Earth as a "water" planet, the scarcity of water in the inner solar system is well illustrated by the fact that all of the Earth's oceans make up less than 0.01% of the Earth's mass. It has been estimated, however, that the amount of water presently incorporated into hydrated minerals in the Earth's interior may be several times as much as currently is found in the oceans.

A logical question for comparative planetology is whether similar processes operating at Venus and Mars resulted in comparable amounts of retained volatiles. The comparison would be expected to be best between Venus and Earth, since the two planets are comparable in size (radius of 6370 km for Earth versus 6050 km for Venus), distance from the sun (1 AU for Earth versus 0.7 AU for Venus), and initial composition (with comparable volatile depletions). These similarities led many scientists to believe that Venus would resemble an early Earth, with oceans, swamps, plants, and animals, until spacecraft observations in the 1960s showed surface temperatures over 700° K (hot enough to melt lead), surface pressure of around 90 atmospheres (with 97% CO_2), and with only barely detectable amounts of water vapor in the atmosphere. Clearly, either Venus and Earth started with totally different volatile inventories, or very different processes occurred at the two planets during the last 4.5 billion years, or both.

Let us leave the questions about Venus temporarily and consider the same questions about Mars. Mars is a smaller planet than Venus and Earth, implying that interior processes might have been somewhat different. Telescopic observations from Earth showed waxing and waning of polar ice caps on Mars with changing seasons, and revealed large-scale features on the surface, including the largest volcanoes and the largest canyon in the solar system. In 1976, observations by the Viking Orbiters and Viking I and II Landers showed the surface of Mars to be a very cold, dry desert with a very thin CO_2 atmosphere. The present combination of low temperature and low pressure does not allow water to exist in liquid form at the surface of Mars. However, thousands of high-resolution photographs taken by the Viking Orbiters showed many surface features (channels and canyons) that could best be explained by very large volume flows of water across the Martian surface in the past. The largest canyon, Valle Marineris, would stretch from New

York to Los Angeles if placed on Earth, and is several times deeper and several times wider than the Grand Canyon. Estimates of the peak volume water flows necessary to produce it rival by far the flows of any river on Earth, including the Amazon, and even greatly exceed the tidal water flows through the Straits of Gibraltar. Thus the question of the initial volatile inventory at Mars appear to have the answer that Mars must have had a large amount of water, and by inference, carbon dioxide in its early history.

Up to this point, the results of comparative planetology have indicated two contradictions: First, that Venus, nearly a twin planet to Earth, seems to be so different in its initial volatile inventory, and second, that Mars, which would be expected to be the most different, appears to be the most similar in its initial volatile inventory. However, closer scrutiny of Venus reveals that the contradiction may be an illusion resulting not from initial volatile inventory, but from subsequent volatile (water) loss.

Let us first examine our expectation that the extreme similarities between Venus and Earth should have produced similar volatile inventories from the outgassing of their interiors. On Earth, volcanic outgassing produces mainly water and carbon dioxide in roughly equal amounts. The cumulative amount of water outgassed is roughly the water content of the oceans, since water loss from the Earth is negligible. The average ocean depth is about 1 km, at which point the pressure is 100 atmospheres, nearly the same as the surface pressure of 90 atmospheres at Venus. The total amount of N_2 in the atmosphere of Venus is about the same as that in the atmosphere of Earth, so the remaining questions are: what happened to the CO_2 outgassed at Earth and what happened to the water outgassed at Venus? The answer to the first question is straightforward. In the presence of liquid water, gaseous CO_2 reacts with calcium and magnesium in rocks to produce calcium and magnesium carbonate (chalk, limestone). This is the process which produces stalagmites and stalactites underground. The resulting precipitates have been laid down in sedimentary formations worldwide (white cliffs of Dover, etc.), and careful inventory of the amount of CO_2 tied up in these deposits gives a result of approximately 100 atmospheres of CO_2 (nearly the same amount as in the present atmosphere of Venus). However, this result does not directly address the question of the initial water inventory at Venus since we have no way of knowing the relative amounts of water and carbon dioxide outgassed by volcanoes at Venus. In fact, a measurement made at Venus by the Orbiter Neutral Mass Spectrometer aboard the Pioneer-Venus Orbiter Spacecraft indicates that Venus has lost most of its initial water inventory, and that the initial amount was only a small fraction of that at Earth.

The definitive measurement was of the deuterium-hydrogen ratio in the atmosphere of Venus. Deuterium, or heavy hydrogen, is a hydrogen atom with a proton and a neutron in its nucleus, giving it twice the mass of ordinary hydrogen. At the top of a planetary atmosphere, ordinary hydrogen concentrations are enhanced relative to deuterium, allowing greater loss of lighter ordinary hydrogen than heavier deuterium, enhancing the deuterium-hydrogen ratio in the atmosphere. Since the initial cosmic abundance of hydrogen and deuterium is known, comparison of the deuterium-hydrogen ratio at Venus allows calculation of how much hydrogen (and hence water) has escaped over geologic time. The measured enhancement at Venus implies that Venus has lost the equivalent of a planetwide ocean with a depth of 20–30 m in the last 4.5 billion years. This would imply an initial water amount less than 3% of Earth's. However, if this is correct, then Venus could have had an ocean for perhaps one billion years. Only after liquid water ceased to exist on the surface would the cycling of CO_2 into carbonate rocks cease, with the build-up of atmospheric CO_2 and a runaway greenhouse effect resulting in present conditions at Venus. It should also be noted that differences in early volatile inventories could arise after the inner planets cooled sufficiently to retain atmospheres through cometary impacts with Venus, Earth, and Mars.

Volatile loss processes in the inner solar system. From the foregoing discussions, we are left with two issues: Why has Earth been able to retain so much water, and what happened to the water that was apparently once present at Venus and Mars? Let us return to comparative planetology in search of answers, and start with some physical characteristics of Earth. The Earth has retained enough heat in its interior from radionuclide decay to have a molten metallic outer core. Earth's rotation produces differential rotation within the molten core, generating a planetwide dynamo magnetic field. This geomagnetic field produces a protective "bubble" approximately 10 Earth's radii in radius which very effectively shields the Earth's atmosphere from the solar wind. Venus, which is nearly the same size as Earth, likely also has a molten outer core, but Venus rotates so slowly (retrograde) that it does not produce a dynamo magnetic field. Observations from the Pioneer-Venus spacecraft in 1978 showed the complete absence of a planetary magnetic field at Venus, and also showed that the solar wind interacts directly with the ionosphere and neutral atmosphere of Venus. Mars, which rotates at about the same rate as Earth, would be expected to produce a dynamo magnetic field if it also had a differentially rotating molten core. However, Mars is a much smaller planet (radius 3400 km) with lower internal heat and faster cooling rate than Earth or Venus and, until recently, it was not known whether its core might still be molten. In 1998, the Mars Global Surveyor spacecraft was inserted into orbit around Mars and found no planetwide dynamo magnetic field, indicating an absence of a molten core. However, at lowest altitudes over certain portions of the Martian terrain, the spacecraft magnetometers measured very strong magnetic fields originating in the Martian crust. The crustal magnetization strongly resembles remnant crustal magnetic fields on Earth produced when iron-bearing lava solidifies within the Earth's magnetic field. The interpretation was obvious: Although Mars no longer produces a dynamo magnetic field because its core has solidified, in the past when the outer core was still molten, it produced a strong planet-wide dynamo magnetic field whose remnants are still preserved in the crustal rocks. Such a strong magnetic field would have shielded the Martian atmosphere from direct interaction with the solar wind.

Many more months of mapping the Martian crustal magnetic fields by Mars Global Surveyor produced a remarkable result: The crustal magnetic fields were confined to the most ancient and heavily-cratered terrain on Mars. Martian terrain has long been divided by Earth-bound observers into two types, one being the heavily-cratered ancient terrain mentioned above, which is mainly confined to the southern hemisphere and low-latitude northern hemisphere of Mars, and the other much smoother terrain judged to be of more recent origin by virtue of very small numbers of impact craters. This second area also includes the highland of the Tharsis bulge where the large volcanoes, including Olympus Mons, are located and extends to the north pole of Mars. The strong contrasts between these two types of terrain on Mars has led to the idea of a dichotomy boundary, an imaginary line running completely around Mars separating the two types of terrain. The confinement of the crustal magnetic fields below the dichotomy boundary has an obvious interpretation. The magnetic dynamo at Mars ceased before the lava flows above the dichotomy boundary solidified, producing the smooth crustal region without remnant magnetism. Knowing from crater counts that the ancient terrain is more than 3.5 billion years old, we can date the cessation of the Martian magnetic dynamo to roughly that time (Figure 1).

In addition to discovering details of the magnetic dynamo history at Mars, other instruments aboard Mars Global Surveyor discovered important mechanisms related to volatile loss. Since the Martian dynamo ceased 3.5 billion years ago, the solar wind has interacted directly with the Martian atmosphere in an interaction nearly identical to that at Venus. This interaction at Mars and Venus impedes and slows the supersonic solar wind, resulting in a strong magnetohydrodynamic (MHD) shock ahead of these planets which deflects most of the postshock solar wind around them. The shocks also heat solar wind protons and electrons, which interact with the upper neutral atmospheres (exospheres) of these planets. The Electron Reflectometer Experiment on Mars Global Surveyor observed significant changes in the fluxes of post-shock electrons at altitudes of nearly 1000 km, indicating that these electrons were colliding directly with hydrogen and oxygen atoms in the Martian exosphere. The specific changes in fluxes as a function of energy allowed us to infer that the electrons were producing hydrogen and oxygen ions by electron impact ionization, and by measuring the changes in electron fluxes, it was possible to calculate the rate of ionization of exospheric neutrals. Since these ions were being produced in postshock solar wind flow around the planet, they were being picked up by the flow and carried away from the planet. Extrapolation of these loss rates over the entire area of the Martian exosphere produces an estimated rate of water loss from Mars equivalent to a 5-m planetwide ocean depth per billion years. In the 3.5 billion years since the Martian dynamo magnetic field last protected the Martian exosphere from the solar wind, Mars has lost the equivalent of nearly 20 m planetwide ocean depth to the solar wind. Since the solar wind interactions with Venus and Mars are so similar today, we may also estimate the total water loss from Venus. With a comparable loss rate to Mars, after 4.5 billion years without a magnetic field, Venus would have lost 20–30 m planetwide ocean depth, in general agreement with results inferred from the Pioneer-Venus deuterium-hydrogen ratio.

Conclusions. It appears that comparative planetology offers significant insights to understanding conditions necessary for retention of volatiles, especially water, by planets. Perhaps the most important is the previously unrecognized role of planetary dynamo magnetic fields in shielding the exosphere from solar-wind induced volatile loss. Over long time scales, these results also relate to the possible existence of life on terrestrial planets in our galaxy. From isotopic evidence of life in the oldest rocks (3.85 billion years) on Earth, it seems that life first appeared only a few hundred million years after the oceans formed on Earth. Model calculations show that Venus could have had an ocean for nearly one billion years, and recent discoveries at Mars indicate a possible shoreline extending around a large ocean which existed billions of years ago on that planet. Such an ocean might also have persisted for more than one billion years, raising the possibility of at least primitive life forms on Venus and Mars in the distant past. Although no record relevant to that question survives at Venus, in the case of Mars many questions remain. Recent findings by the Mars Express spacecraft indicate that subsurface deposits of water near the Martian south pole contain enough water to make a planetwide ocean 11 m deep. If the solar wind loss estimate is correct, this means that Mars has retained nearly one-third of its original water inventory. A neutron spectrometer on the Mars Odyssey spacecraft indicated some subsurface water nearly everywhere at Mars. At present, the thin Martian atmosphere allows solar extreme ultraviolet (EUV) radiation to strike the Martian surface, rendering it sterile and breaking down even the simplest molecules. But at Earth, our biosphere extends several kilometers underground, with primitive microorganisms living in water-filled pores in rock. If life arose in an early Martian ocean, it would not be surprising to find subsurface life there today.

Suggested reading. *Venus* by Hunter et al. (University of Arizona Press, 1983). “Magnetic field and plasma observations at Mars: Preliminary results of the Mars Global Surveyor Mission” by Acuna et al. (*Science*, 1998). “Venus-like interaction of the solar wind with Mars” by Cloutier et al. (*Geophysical Research Letters*, 1999). “Evidence for electron impact ionization in the magnetic pile-up boundary of Mars” by Crider et al. (*Geophysical Research Letters*, 2000). “Subsurface radar sounding of the South Pole layered deposits of Mars” by Plaut et al. (*Science*, 2007). TLE

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