NOTES AND CORRESPONDENCE

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Water on/in Mars and the Moon

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Abstract

The speculation of an ancient ocean, river and lake on Mars, the observation of geological features and the findings of H_2O on the Martian surface, and the detection of a “water lake” beneath 1.5 km in Mars are all consistent with the scenario of water envisaged earlier by Liu (Phys Earth Planet Inter 49: 142–167, 1987; Icarus 74: 98–107, 1988). Unless sealed in cavities, liquid water or naked ice should not survive on the Martian surface. These materials cannot possibly exist on the lunar surface either, regardless of the recent claims made by space missions to the Moon, because the lunar mass is even much smaller than Mars. Both the disappearance of the Martian ancient ocean and the scarcity of the findings in the space missions manifest that water and ice are not physically stable on the surface of Mars and the Moon. Otherwise, significant amounts of water and/or ice should have had been accumulated during the long history of these planets. Depending on the origin, the Moon may or may not contain ordinary hydrous minerals. Whether a volatile can stably exist on the surface of a planet, in either liquid or solid, depends on whether the volatile can exist as a component of the planet’s atmosphere.

Key points

- Water or ice is physically unstable on Mars and the Moon.
- Water is likely entrapped inside Mars, but not the Moon.
- Volatile stable on planet should also be a component of planet’s atmosphere.

Keywords: Water, Mars, Moon

1 Introduction

If the Moon can be treated as a planet, Mars and the Moon are the two coldest planets among the terrestrial planets (Mercury, Venus, Earth, Moon and Mars), though the temperature can reach $\sim 125^\circ\text{C}$ on the sunlit Moon. There are only two competing factors for a planet to hold a volatile species like H_2O on the surface or in the atmosphere. These are.

1. the surface temperature and/or pressure of a planet and
2. the total mass, or the gravity/attraction force, of a planet.

The surface temperature and/or pressure of a planet determine the state of the species, i.e., whether a volatile species exists as a solid, liquid, or gas on the surface of a planet. The temperature also is a competing factor with the gravity force to hold a gas species in an atmosphere. It is the kinetic energy of temperature that causes a gas species to escape from the atmosphere of a planet. The higher the temperature, or the lighter the gas species, the faster a gas species escapes from an atmosphere. Thus, the temperature factor favors Mars and the Moon to have volatiles like H_2O on their surface because they are the coldest terrestrial planets. On the other hand, the more powerful competing factor of mass or gravity force is not in favor of these two planets because of their small masses.

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Table 1 Comparison of the lower bounds of the CM for various gas species with the mass of Mercury, Venus, Earth, Moon and Mars and their respective atmospheric composition and surface pressure

Gases (molecular weight)	Critical Mass (g)	Planets	Mass (g)
		Moon	7.35×10^{25}
		Mercury	3.30×10^{26}
			($O_2 + Na + H_2 + He = 10^{-15}$ bar)
CO ₂ (44.01)	3.30×10^{26}		
Ar (39.95)	3.64×10^{26}		
O ₂ (32.00)	4.54×10^{26}		
N ₂ (28.01)	5.19×10^{26}		
CO (28.01)	5.19×10^{26}		
		Mars	6.419×10^{26}
			($CO_2 + N_2 + Ar = 8 \times 10^{-3}$ bar)
H ₂ O (18.02)	8.06×10^{26}		
CH ₄ (16.05)	9.05×10^{26}		
He (4.00)	3.63×10^{27}		
		Venus	4.869×10^{27}
			($CO_2 + N_2 = 93$ bar)
		Earth	5.976×10^{27}
			($N_2 + O_2 + H_2O + Ar = 1.013$ bar)
H ₂ (2.02)	7.19×10^{27}		
		Uranus	8.68×10^{28}
			($H_2 + He = ??$)

1.1 Water on Mars

An atmosphere is defined as a layer of gases around a material body that are mainly attracted by the gravity of the material body and retained for a long duration. A volatile like H₂O can be a gas in an atmosphere and liquid water or solid ice on the material body depending upon the surface temperature and pressure. In order to discuss water on Mars, one must take into consideration the role of gaseous H₂O in the atmosphere.

The minimum planetary mass required to retain a given gas species as a component of an atmosphere was defined as the critical mass (CM) of the planet for that gas species by Liu (2014). CM is gas species dependent, and is somewhat inversely proportional to the molecular weight of a gas species. The lower bounds of CM for various common gas species of the planets in our Solar System were estimated by Liu (2014) and are given in Table 1. Thus, the true values of CM must be greater than those listed in Table 1. The mass of all terrestrial planets and that of Uranus, the least massive major planets, and their atmospheric composition and surface pressure are also given in Table 1 for comparison. For simplicity, atmospheric gases less than 1% are not shown and the gas species are listed in the order of decreasing abundance.

Both CM's and the mass of planets are listed in order so that one is able to see what gas species can be retained in the planet's atmosphere based on the calculated CM's. Except for He, Table 1 shows that the calculated lower bounds of CM are consistent with the atmospheric composition of all planets observed. That Table 1 suggests that both Venus and Earth might be able to retain He in their atmospheres is merely an artifact. The fact that the Earth is not massive enough to hold He in its atmosphere (Fegley 1995) suggests that the true CM for He should be greater than 5.976×10^{27} g.

Table 1 clearly shows that the mass of Mars (6.419×10^{26} g) is significantly smaller than the lower bound CM for H₂O (8.06×10^{26} g). In other words, gaseous H₂O is not able to exist on the Martian surface for a long duration, or Mars is never massive enough to hold gaseous H₂O in its atmosphere. Today's atmospheric composition of Mars (CO₂, N₂, Ar, O₂, and CO) and the absence of H₂O, CH₄, He, and H₂ in the Martian atmosphere are in complete agreement with the lower bounds of CM's calculated and listed in Table 1.

Today's surface temperature of Mars is well below the melting temperature of H₂O. Therefore, it is impossible for liquid water to be present on the Martian surface. Actually, even the naked H₂O ice cannot exist on the Martian surface either because sublimation would soon remove all the ice. This conclusion, however, appears to be in contradiction with many observed morphologic features of Mars and the recent NASA missions to Mars. Squyres (1984) and Carr (1986) have long speculated that many surface geological features of Mars suggest the existence of an ancient ocean on Mars. The NASA 2008 and 2016 missions confirmed the existence of H₂O ice in the Martian soil. Based on photos taken by Perseverance rover, an ancient delta-lake system and flood deposits have been speculated at Jezero crater on Mars by Mangold et al. (2021). It was inferred that Jezero crater itself was an ancient lake, which was connected to a sizeable river. The latter, in turn, implies that there was an ancient ocean on Mars as advocated earlier by Squyres (1984), Carr (1986), and Liu (1988). The disappearance of an ancient ocean, river and lake on Mars appears to contradict to the earlier NASA claims of H₂O ice in the Martian soil, unless H₂O ices were sealed in some kinds of cavities in the Martian soil as suggested by Liu (2014).

Liu (2014, 2019) also concluded that the Martian H₂O on the surface should be inherent, or was derived from its interiors, and cannot be added by "dirty snowballs" after accretion, because Mars is never massive enough to retain gaseous H₂O in its atmosphere. Any H₂O added by snowballs would be evaporated and lost to outer-space during bombardment.

1.2 Water in Mars

In order to envisage the possible sources of Martian water, one must look into water inside Mars. It is assumed that all terrestrial planets were accreted from similar primordial planetesimals, containing a small amount of hydrous minerals, and via similar accretion processes. Hydrous minerals are commonly found in many stony meteorites on the Earth's surface today. During an early stage of accretion, the collisions among planetesimals and the impact of planetesimals onto the infant planets had to be small. As envisaged by Liu (1988, 2019), hydrous minerals should remain intact and H₂O should have been buried inside a growing planet when the impact pressure was less than ca. 600 kbar. Dehydration starts to occur above this pressure and H₂O in the infalling planetesimals and the surface hydrous minerals would be released to incorporate in a proto-atmosphere. Continuous growth of the planets would cause a total release of H₂O from hydrous minerals. In the case of Mars, all released gaseous H₂O would then escape from the growing Mars to the outer-space, and be gone forever, because it has been said that Mars is not massive enough to retain gaseous H₂O in its atmosphere.

The total H₂O buried inside the growing Mars after dehydration was completed is estimated to be 1.4×10^{24} g by Liu (1988). This amount of water is nearly the same as that of today's Earth oceans estimated by Holland (1984). Liu's (1988) estimate was based on the impact dehydration model proposed by Lange and Ahrens (1984), assuming that the H₂O content of the infalling planetesimals is 0.33 wt%.

The growth of a planet is also complicated by the presence of a "magma ocean" during accretion. Hofmeister (1983) and Matsui and Abe (1986) suggested that, due to impacting, Earth's surface commenced formation of a "magma ocean" when the growing Earth exceeded ~40% (a radius of ~2550 km) of its final radius. This hypothesis should also be applicable to Mars because the Martian radius exceeds 2550 km. Thus, after accretion ceased, Mars should be enveloped with an 845-km thick "magma ocean". When an impactor hit the magma ocean on a growing planet, instead of producing large quantities of impact-induced dusts and releasing volatiles to the proto-atmosphere as would be expected in a solid-solid impact, an impactor would penetrate into the magma ocean to greater depths. High-pressure experimental studies indicate that at least 6 wt% H₂O can be dissolved in silicate melts at 3 kbar and the solubility increases with increasing pressure for all silicate melts known (Liu 1987). Thus, the earlier estimate of 1.4×10^{24} g H₂O buried inside Mars should be regarded as the lower bound, if the "magma ocean" hypothesis is also taken into consideration.

Ordinal hydrous minerals such as serpentine (or chrysotiles), talc and mica are stable only at the near surface regions of the Earth. They are stable at temperatures below ca. 700–800 °C and at pressures below ca. 30–35 kbar. Thus, before the 1980's most earth scientists believed there is no water in the deep inside of the Earth. On the other hand, several dense hydrous magnesium silicates (DHMS) were synthesized in high pressure experiments, noticeably the 10 A-phase and phase-A, -B, -C and -D, between mid-1970's and mid-1980's.. The significances of these DHMS to the mantle mineralogy of the Earth were, however, first explored by Liu (1985, 1986, 1987).

Liu (1988) compared today's Martian temperature profile proposed by Toksoz et al. (1978) with the Earth's mantle solidus determined by Kushiro et al. (1968) and the water line,

forsterite water enstatite phase A

derived by Liu (1987), see Fig. 1. Also shown in Fig. 1 is the temperature profile of the Earth for comparison. Because both the mantle solidus and the water line were determined in high pressure experiments, the temperature profiles of both Mars and the Earth have also been plotted against pressure for comparison. The pressures in the Martian interior are very small compared with those inside the Earth. Thus, in Fig. 1, the thermal gradient inside Mars is found to be steeper than that inside Earth at pressures less than 50 kbar, though the temperature inside the Earth is higher everywhere than that inside Mars at the same depth.

Because of the greater uncertainty inherent to the thermal models, Mars in particular, one should probably not take the precise values of these models too seriously. However, Fig. 1 does offer some interesting features when these models are compared with the mantle solidus. Figure 1 shows that the Martian temperature profile intersects the solidus near 230 and 580 km whereas that for Earth does not intersect the solidus. In other words, there probably exists a partial melting zone inside Mars, but such a zone does not exist inside Earth.

The Martian thermal profile intersects the water line with 10% FeO near 800 km whereas the Earth's thermal profile intersects the water line near 320 km. H₂O below the water line would be retained in various DHMS, which act as water reservoirs in the deep parts of these planets. Above the water line, supercritical H₂O fluid is freely moving upwards and forms ordinary hydrous minerals near surface regions, when the P–T conditions and chemical environments are suitable, and the remaining

unreacted water would form oceans on the surface via degassing processes. Except above 230 km, nearly all of the free supercritical H_2O fluid above the water line in Mars would dissolve in the silicate melts between 230 and 580 km today.

We now envisage a scenario which describes the evolution of H_2O during solidification of Martian magma ocean after accretion. After accretion, it is conceivable that Mars may have had a temperature profile such as XY shown in Fig. 1. XY intersects the mantle solidus at point M, or the bottom of the magma ocean at a depth of 845 km, and the water line at point B (a depth of 905 km). Below the water line H_2O would be stored in phase A and above the water line supercritical H_2O fluid would freely move upwards, dissolving in the magma ocean, because no ordinary hydrous minerals are stable above 40 kbar. On cooling, the near surface regions of Mars should have cooled the fastest and solidified first. If the gradient of XY is less than that of the mantle solidus, Mars also solidified from inside out and H_2O above 905 km would be entrapped inside to form a partial melting zone. On further cooling, the volume of the partial

melting zone decreases and the concentration of H_2O in the partial melting zone increases due to further solidification. It is conceivable that H_2O contained between 905 and 580 km would be dissolved in today's partial melting zone between 580 and 230 km. Thus, today's partial melting zone would contain about 7.83×10^{23} g H_2O , which is equivalent to 0.59 wt% H_2O in today's partial melting zone. These figures were calculated by assuming that the average density is 3.2, 3.4 and 3.6 g/cm³, respectively, above 230 km, between 230 and 580 km and between 580 and 905 km and 0.33 wt% H_2O in the infalling planetesimals and the magma ocean. The 0.59 wt% H_2O is an order of magnitude below the amount of H_2O that can be dissolved in silicate melts determined in high-pressure experiments mentioned earlier (Liu 1987). In other words, only H_2O above 230 km in the magma ocean is able to escape upwards either to form ordinary hydrous minerals in the near surface regions of Mars or to form Martian ocean on the surface.

The total H_2O that escaped from above 230 km is estimated to be 3.1×10^{23} g, which is capable of forming a 2-km Martian hydrosphere, if no ordinary hydrous minerals were formed above 230 km during solidification. There should be some ordinary hydrous minerals in the near surface regions of Mars, but it is very difficult to estimate the amounts without further missions to Mars. The long speculated ancient Martian ocean could only occur at very early stage after solidification via degassing process. Whether there was an ancient ocean on Mars depends on how quickly water was supplied via degassing process and how soon water was vaporized. In any case, an ancient ocean would not survive for long because Mars is not massive enough to hold gaseous H_2O in its atmosphere.

By analyzing the radar information collected by Mars Express between May 2012 and December 2015, ESA announced in July 2018 that there exists a 20 km wide very bright reflective surface below 1.5 km in the Martian southern pole. After excluding all other possibilities, ESA concluded that it is highly likely that there is a water lake beneath the bright reflective surface, though the radar data are not able to detect the thickness of the lake and other details. The possible existence of the water lake below 1.5 km announced by ESA is consistent with the H_2O scenario just outlined earlier. If the water lake indeed exists, the lake must be highly contaminated with mud and other minerals, either dissolved or suspended, just like highly concentrated "brine".

1.3 Water on the Moon

The lunar mass is 7.35×10^{25} g, which is nearly one order of magnitude smaller than that of Mars. Thus, the Moon is far less massive than Mars to hold gaseous H_2O in its

atmosphere. As a matter of fact, the Moon has virtually no atmosphere at all ($\sim 10^{-15}$ bar atmospheric pressure), which would be expected from the CM's for all common gas species listed in Table 1. Then, what is it about water on the Moon? In principle, there should be neither liquid water nor naked ice on the lunar surface, as we have elucidated earlier for Mars.

On the other hand, NASA's several recent missions to the Moon pointed out the opposite results. The mission of Lunar Prospector detected concentrated H_2 molecule in the lunar poles in 1998. Three missions (including Chandrayaan-1) to the Moon in 2009 found that OH^- is everywhere and concentrated in the poles. Li et al. (2018) provided the direct evidence of surface exposed water ice in the permanently shaded poles from studies at Stratospheric Observatory for Infrared Astronomy (SOFIA). Not only water ice was found in the permanently shaded poles with temperatures in the vicinity of -170°C , molecular water was also detected on the sunlit Moon with temperatures in the range $70\text{--}80^\circ\text{C}$ by Honniball et al. (2021) at SOFIA. The latter study found that the sunlit lunar surface is covered by a few hundreds of ppm H_2O nearly everywhere.

Until further confirmations are available, however, we should be rather skeptical of accepting these results. A possible scenario is that H_2 may come from the solar wind, OH^- from surface hydrous minerals or in the impact glasses, and water/ice from H_2O entrapped as inclusions in the impact induced glasses, e.g., tektites. The latter are commonly found on the lunar surface as a result of meteorite or asteroid impact.

1.4 Water in the Moon

Whether there is water inside the Moon depends very much on the origin of the Moon. There are various models concerning the origin of the Moon. We focus our discussion at two models, i.e., accreted and impacted.

If the Moon was accreted, simultaneously with other terrestrial planets, from similar primordial planetesimals via similar accretion processes like Mars described earlier, the whole Moon should contain 0.33 wt%, or 2.43×10^{23} g of H_2O . It is simply because the impact pressure on the Moon during accretion has never exceeded 600 kbar and the magma ocean has never occurred on the Moon. The central pressure for the Moon is less than 50 kbar and the water line does not exist inside the Moon either. All 2.43×10^{23} g H_2O ought to be preserved in ordinary hydrous minerals at pressures below 40 kbar. Tektites and other impact glasses may be added throughout the history to the lunar surface after accretion.

Modern theory on the origin of the Moon leans towards the giant impact hypothesis (e.g., Benz et al. 1986, 1987). The Moon might be formed by a striking

from a Mars-like impactor at a very early stage of the Earth's evolution. The consequences of the Moon-forming giant impact should at least be as follows (see Liu 2019):

1. The Earth acquired the Moon (e.g., Benz et al. 1986, 1987);
2. The iron core of the impactor was incorporated into Earth's interior as shown in the computer simulation (Liu 1992);
3. The release of most of the Earth and impactor volatiles into the CO_2 -rich proto-atmosphere. It is highly likely that the Earth was not completely solidified before its capture of the Moon. Most, if not all, H_2O dissolved in the entrapped magma ocean, somewhat like today's Venus and Mars, escaped into the Earth's CO_2 proto-atmosphere.

The Moon was accreted from ejected debris after the giant impact. If Earth's magma ocean and/or hydrous minerals contained in the original planetesimals were also incorporated in the formation of the Moon, then there should be H_2O inside the Moon today. Otherwise, the Moon itself has no H_2O and any surface H_2O was from impact meteorites and/or glasses added to the Moon after the second accretion. As mentioned earlier, the impact pressure on the Moon never exceeds 600 kbar and no dehydration takes place during impact. Thus, any H_2O in the lunar surface hydrous minerals and in the impactors of meteorite and/or glass would have been preserved after impact.

Liu (2004, 2019) proposed that the Earth's proto-atmosphere should be composed of more than 95% CO_2 , like Venus and Mars. Today's atmospheric compositions of both Venus and Mars are nearly identical. There are no compelling reasons that the Earth's atmosphere should be so drastically different from those of Venus and Mars while the Earth is located in between. The impact origin of the Moon should be the most viable mechanism that changed the Earth's atmospheric compositions after the giant impact (Liu 2009, 2019).

2 Conclusion

The speculated ancient ocean, river and lake on Mars had apparently totally disappeared long ago. This manifests that neither water nor ice is physically stable on Mars as concluded earlier by Liu (2014, 2019) that Mars is never massive enough to hold the gaseous H_2O in its atmosphere. The scarceness of either liquid water or naked ice claimed in various space missions to Mars and the Moon also points to that these materials are not physically stable on the surface of Mars and the Moon. Otherwise, significant amounts of water and/or ice should have had been

accumulated throughout the long history of these planets and should have been found everywhere today. A small quantity of OH^- or H_2O may chemically be preserved in hydrous minerals or impact glasses and water or ice may form inclusions in impact glasses. All these conclusions are in support to the scenario of water on Mars and the Moon envisaged earlier by Liu (1988, 2009, 2014) and in this study. Finally, in turn, one may also conclude that whether a volatile species can stably exist on the surface of a planet, in either liquid or solid, depends on whether the volatile can exist as a component of the planet's atmosphere. This appears to be true in the cases of Mars and the Moon.

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Authors' contributions

The author read and approved the final manuscript.

Declarations

Competing interests

The authors declare that they have no competing interests.

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