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Atmospheres and Oceans of Terrestrial Planets

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ABSTRACT

The atmospheres and oceans of the terrestrial planets are primarily made up of the two most abundant volatiles, CO_2 and H_2O. The possible sources and early evolutions of these volatiles during accretion are briefly elucidated. The total mass, or the gravity force/attraction force, of a planet plays the most important role to determine whether an atmosphere and/or ocean can exist on a planet. Both the Moon and Mercury are not massive enough to hold CO_2, the heaviest natural volatile, to form an atmosphere. Thus, their atmospheres are virtually in vacuum (manifested by its atmospheric pressure of ~10^{-15} bar). Mars is not massive enough to hold H_2O in its atmosphere. Therefore, Mars cannot sustain an ocean for a long period of time. On the other hand, observed geological features on Mars suggest that there were possible ancient oceans on Mars. The scenario of the origin of an ancient Martian ocean is postulated. Both Mars and Venus possess basically the same atmospheric composition with more than 95% CO_2 and followed by a few percent of N_2, which are consistent with the estimated critical mass (CM) for these volatiles. Earth is situated between Venus and Mars, but possesses a very different atmospheric composition. During accretion, however, there is no compelling reason that the Earth's proto-atmosphere should be any different from those of Venus and Mars. It has been postulated that the occurrence of the Moon by a strike of a Mars-like impactor in the early stage of Earth's life after solidification, the so-called Moon-making giant impact theory, also generated the indigenous hot soda oceans on the Earth. Further on the way of cooling, the growth of the indigenous ocean would somewhat remove CO_2 from the Earth's proto-atmosphere. The removal was later accelerated and completed when the indigenous oceans reacted with plagioclase, the most abundant mineral on the Earth, to form carbonate and clay minerals. Once CO_2 was removed from the Earth's proto-atmosphere, N_2 naturally becomes the most abundant component in the Earth's atmosphere as observed today.

Keywords: atmospheres, oceans, terrestrial planets.

INTRODUCTION

The origin and early evolution of the atmospheres and oceans of terrestrial planets are classic unsolved problems in planetary sciences. These topics are also of great interest to science in general and have attracted attention from science philosophers, who have considered life in nature. Nearly all theories concerning these topics are model dependent and constrained by various evidence and investigations (e.g., Holland, 1984; Kasting and Ackerman, 1986; Pepin, 1991; Liu, 2004; 2009). It is widely known that our Solar System consists of 4 inner terrestrial planets (Mercury, Venus, Earth+Moon and Mars) and 4 outer major planets (Jupiter, Saturn, Uranus and Neptune). The atmospheres of the major planets are exclusively composed of H_2

and He with slightly different ratios. The atmospheres of the terrestrial planets appear to be somewhat irregular. Except for the Earth, however, in reality, the atmospheric compositions of the terrestrial planets are also rather similar; both Venus and Mars are composed of more than 95% CO_2 and followed by a few percent of N_2 and Mercury is virtually in vacuum due to its small mass. Thus, it appears that the Earth's atmosphere is the only abnormality in our Solar System, in particular the Earth is situated between Venus and Mars and the latter two have nearly an identical atmospheric composition.

H_2O and CO_2 are the two most abundant volatiles on the terrestrial planets. The former forms the Earth's oceans, and the latter constitutes more than 95% of Cytherean and Martian atmospheres. These two volatiles are also the most vital elements (C, H and O) for life on the Earth. It is assumed that all terrestrial planets were accreted from similar primordial planetesimals, containing a small amount of carbonates and hydrous minerals, and via similar accretion processes. Carbonates and hydrates are commonly found in many stony meteorites (e.g., chondrites) on the Earth's surface today. During an early stage of accretion, the collisions among planetesimals and the impact of planetesimals onto the infant planet had to be small. Thus, the growing planets should maintain all carbonates and hydrous minerals in their infant planets. Further, during their growth, the impacting force increased to a stage where decarbonation and dehydration would occur. The latter reactions were experimentally observed by shock-wave studies of carbonates and hydrous minerals (Boslough et al. 1982; Kotra et al. 1983; Lange and Ahrens 1984; 1986). Based on the results of these experimental studies, it can be concluded that the CO_2 and H_2O contained, in carbonates and hydrates had to be buried inside the terrestrial planets (and probably all planets as well for as long as planetesimals contained carbonates and hydrates) during the early stage of accretion before the impact pressure reached over 100 - 200 kbar. Even after decarbonation and dehydration commenced, there should still be some CO_2 and H_2O buried inside the terrestrial planets up until the impact pressure exceeded 600 - 700 kbar, at which point, the total decarbonation and dehydration took place. Assuming that the H_2O content in the infalling materials is 0.33 wt%, Liu (1988) calculated that the total H_2O buried inside Venus, Earth, and Mars should be $\sim 1.4 \times 10^{24}$ g which is equivalent to the mass of today's Earth oceans estimated by Holland (1984).

Atmosphere of a Planet

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. Whether a volatile gas species can form an atmosphere of a planet is determined by the following factors:

1. The availability of a volatile species, either as a compound or as an element, in the nearby area inside or outside of a planet;
2. The surface temperature and/or pressure of a planet; and
3. The total mass, or the gravity force/attraction force, of a planet.

The reason for the first factor is self-evident. If a gas species is not available in the nearby area of a planet, it is not possible to form the atmosphere of a planet. The surface temperature and/or pressure of a planet determines 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 acts as 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. The atmospheric composition of a planet appears to be better determined by the total mass of a planet because the surface temperature drops rather quickly at higher altitudes. A less massive planet may also possess an atmosphere if its surface temperature is sufficiently lower. Nonetheless, there is always some escape of a gas to outer space for as long as the temperature is not zero. Providing the escape of a gas from an atmosphere is negligible, it is regarded as a component of an atmosphere. In rare cases (like Mercury), however, the gases may also be imposed upon by the solar wind. The atmospheric composition of a terrestrial planet is generally related to the chemistry of primordial planetesimals that formed the solid body and the subsequent escape of gases during and after accretion.

The proto-atmosphere is defined as an atmosphere evolved during accretion of a planet. No one knows what the components of a proto-atmosphere should be unless an astrophysicist is able to observe the accretion of a planet in another solar system. Liu (2025) derived a theoretical composition of the terrestrial planets' proto-atmosphere. It is composed primarily of CO_2, Ar and N_2 when the mass of a growing planet becomes greater than 3.30×10^{26} g. This is identical to the atmospheric compositions of Venus and Mars observed today. Therefore, it is highly likely that both Venus and Mars retained their proto-atmospheres until now.

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. In view of the way that the lower bounds of CM were estimated, the smaller the molecular weight the greater the discrepancy between the true values and the lower bounds 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 the Earth's mass, 5.976×10^{27}g. The lower bound CM for H_2 shown in Table 1 is 1.20 times the Earth's mass, and the CM for H_2 was estimated some 5 to 20 times that of the Earth's mass by Mizuno (1980) and Ikoma et al. (2000), respectively. The mass of Uranus is 14.5 times that of the Earth, which suggests that the true value of CM for H_2 must be less than 15 times that of the Earth.

Mercury and the Moon

Table 1 shows that when the mass of a planet grows over 3.30×10^{26} g it would hold CO_2, the heaviest natural volatile, to form the proto-atmosphere of the growing planet. Mercury is not massive enough to hold CO_2 in its atmosphere and thus virtually becomes a vacuum (manifested by its atmospheric pressure of ~10^{-15} bar). The trace amounts of O_2, Na, H_2 and He on Mercury's surface are likely to be a transient and short-lived phenomenon, and H_2 and He may even be imposed by the solar wind.

The mass of the Moon is 22.3% of that of Mercury. Therefore, like Mercury, the Moon is not massive enough to hold CO_2 or any other volatiles listed in Table 1 to form its atmosphere during accretion or growth. Consequently, the Moon should also be in vacuum and has an atmospheric pressure of ~10^{-15} bar. Although the Moon is in vacuum, it does not imply that no volatiles exist in the Moon. Both carbonates and hydrous minerals are likely to be found inside and/or on the surface of the Moon. Water/ice may also be entrapped as inclusions in the impact induced glasses.

NASA's several recent missions to the Moon revealed the evidence of trace amounts of H_2, OH^- and water/ice. The mission of Lunar Prospector detected concentrated H_2 molecules 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 the studies at Stratospheric Observatory for Infrared Astronomy (SOFIA). Not only water, ice was also 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 70–80 °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. On the other hand, just like O_2 and Na on Mercury, the trace amount of H_2O found on the Moon are likely to be a transient and short-lived phenomenon. 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 impacted 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.

Liu (2022) concluded, whether or not volatiles can stably exist on the surface of a planet, in either liquid or solid, depends on whether the volatiles can exist as a component of the planet's atmosphere. Since both Mercury and the Moon are virtually in vacuum, trace amounts of any free water/ice would be unstable, and thus, a transient and short-lived phenomenon.

Mars

In terms of mass, Mars is the third most massive planet among the terrestrial planets. Today's Martian atmosphere is composed of more than 95% CO_2, followed by N_2, Ar, O_2 and CO (in order of decreasing abundance). The absence of H_2O, CH_4, He and H_2 in the Martian atmosphere is in complete agreement with the lower bounds of CM's calculated and are listed in Table 1. The mass of Mars (6.419×10^{26}g) is significantly smaller than the lower bound CM for H_2O (8.06×10^{26}g). In other words, Mars is never massive enough to hold gaseous H_2O in its atmosphere and gaseous H_2O is not able to exist on the Martian surface for a long duration.

Today's surface temperature of Mars is well below the melting temperature of H_2O. Therefore, it is impossible for liquid water to be present on the Martian surface. Actually, even the naked H_2O 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 H_2O ice in the Martian soil. Based on photos taken by the 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, on the other hand, appears to contradict the earlier NASA claims of H_2O ice in the Martian soil, unless H_2O ice was sealed in some kind of cavities in the Martian soil as suggested by Liu (2014).

Liu (2014, 2019) also concluded that the Martian H_2O on the surface should be inherent, or was derived from its interiors, and cannot be added by "dirty snowballs" after accretion, as speculated as the origin of oceans on the Earth by Frank et al. (1986a; b), because Mars is never massive enough to retain gaseous H_2O in its atmosphere. Any H_2O added by snowballs would be evaporated and lost to the outer-space during bombardment.

In order to envisage the possible sources of Martian water, one must look into water inside Mars. As mentioned earlier, an equivalent to the mass of today's Earth oceans was already buried inside Mars during its early stage of accretion. Further on the way of growth, when the Martian radius exceeded over ~2550 km, its surface would have been covered by a magma ocean due to the high temperatures and pressures generated by infalling planetesimals (e.g., Hofmeister, 1983; Matsui and Abe, 1986). Once the magma ocean was formed, the solid-solid impact models of both decarbonation and dehydration become an impact of solid planetesimals into the liquid magma ocean. Not only does the mechanism of a solid-liquid impact differ drastically from those of a solid-solid impact, the silicate melts are also capable of dissolving an appreciable amount of H_2O at high pressures (Liu, 1987). 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% H_2O can be dissolved in silicate melts at 3 kbar and the solubility increases with increasing pressure for all known silicate melts (Liu 1987). However, no appreciable amounts of CO_2 are known to dissolve in silicate melts at high pressures. Thus, nearly all the H_2O released during impacting and penetration would be dissolved in the magma ocean and most of the CO_2 released would escape. In other words, even if the impact pressure exceeded 100 kbar, escape of H_2O from the growing planets and/or loss of H_2O to outer-space would not happen once the surface was covered by a magma ocean. Escape and loss of CO_2 to outer-space, on the other hand, would take place once the impact pressure exceeded 100 kbar regardless of the formation of a magma ocean on the surface during accretion. CO_2 released from decarbonation due to impact had to be retained and formed the proto-atmosphere when the planets grew to over 3.30×10^{26}g. The conclusion that nearly all the H_2O in the infalling planetesimals would be preserved in the silicate melts when they impacted on the magma ocean was also reached by Holland (1984) in his calculation of the solubility of various gases in the molten Earth.

Right after the completion of accretion, the planets must have cooled down and solidified. The magma ocean, on the other hand, is most likely entrapped inside the planet. Liu (2022) showed that the Martian temperature profile intersects the "water line" at a depth near 905 km and its mantle solidus at depths near 230 and 580 km. In other words, there probably exists a partial melting zone between 230 and 580 km inside Mars. It is conceivable that H_2O contained between 905 and 580 km would be dissolved in the partial melting zone. Thus, today's partial melting zone would contain about 7.83×10^{23}g H_2O, which is equivalent to 0.6 wt% H_2O in today's Martian partial melting zone. The 0.6 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). Supercritical H_2O 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 above 230 km would be capable of forming oceans on the Martian surface via degassing processes. 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 2000 m Martian hydrosphere, if no ordinary hydrous minerals were formed above 230 km during solidification. The depth of the ancient Martian ocean was also estimated to be 10~100 m and 500~1000 m by Squyres (1984) and Carrs (1986), respectively, based on their observations of surface geological features on Mars. The estimates of the ancient ocean depth appear to be rather inconsistent, but in reality it is quite the opposite. The estimates are in reasonably good agreement because Liu's (2022) estimate is the maximum initial depth and the ancient Martian ocean was decreasing with time.

The long speculated ancient Martian ocean could only occur at a very early stage after solidification via degassing processes. 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. Based on the observed surface geological features, however, the ancient Martian ocean might still survive for a few millions to tens-millions of years, but, it was probably not long enough to have developed life on Mars.

Venus

The Cytherean atmosphere possesses primarily CO_2 and N_2 plus the clouds that are composed of sulphuric acid and various other corrosive compounds. Ar and H_2O are missing from its atmosphere. In considering the thick CO_2 atmosphere on Venus (90 bar), the small amount of Ar would become trace (<< 1%) and the absence of other gases may simply be due to a lack of availability or even less abundant than Ar. The second abundant N_2 (~3 bar) may be derived from nitrate minerals in planetesimals during accretion when the mass of planets grows over 5.19×10^{26} g.

Venus is known to be deficient in H_2O, relative to Earth, by a factor of 10^4 to 10^5. It has been suggested that nearly all of Venus's H_2O is still entrapped inside the partial melting zone (or the entrapped magma ocean) between 120 and 250 km because Venus may not yet have reached complete solidification (Liu 1988, 2009). However, the total lack of H_2O in the Cytherean atmosphere may also imply that the lower bound of CM for H_2O listed Table 1 is under estimated and that the true value of CM for H_2O should be greater than the Cytherean mass of

4.869×10^{27} g. In other words, both Mars and Venus are not massive enough to hold gaseous H_2O in their atmospheres.

The proto-atmosphere of Venus during and immediately after accretion should be composed primarily of CO_2 that was released due to decarbonation after Venus grew to over 3.30×10^{26} g. Some amount of H_2O should also later be added to the Cytherean proto-atmosphere once solidification of a magma ocean had started. The amount of H_2O released due to solidification from the top 120 km of the Cytherean mantle throughout the life of Venus is probably rather small, because the large-scale internal silicate melt would act like a sponge that absorbs all free H_2O. In view of today's high surface temperatures on Venus (~460 ^{o}C), it is quite conceivable that the internal mantle temperatures of Venus are most likely higher than those of the Earth at the same depth. Both the high surface temperature and the lack of H_2O in its atmosphere indicate that oceans probably have never occurred on Venus throughout its life.

The observed atmospheric compositions of Venus and Mars are composed of more than 95% CO_2. This appears to suggest that both Venus and Mars might have maintained their proto-atmospheres until now (see also Liu, 2025). Earth is situated between Venus and Mars, thus there is no compelling reason that the Earth's proto-atmosphere should be any different from those of Venus and Mars. Then what has happened to the CO_2-dominated Earth's proto-atmosphere?

Earth

It is obvious that the atmospheric composition of the Earth (78%N_2, 21%O_2, 0.9%Ar, and others) is totally different from those of the other terrestrial planets, not to mention all other major planets in our Solar System as well. So, the Earth is odd and unique in itself. The Earth is not only abnormal in its atmospheric composition, but also in possessing the oceans, the largest satellite, and the greatest average density (Liu, 2023).

Earth's large Moon (relative to Earth's mass) is generally believed to be formed by a strike from a Mars-like impactor at a very early stage of the Earth's evolution, the so-called Moon-forming giant impact hypothesis (e.g., Benz et al. 1986, 1987). Whilst the rocky debris formed the Moon, the giant impact also released most of the Earth's volatiles into its 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 interiors of Venus and Mars, escaped into the Earth's CO_2-rich proto-atmosphere.

The partial pressure of CO_2 in the proto-atmosphere of the Earth was estimated to be 114 bar by Liu (2009) and today's Cytherean atmospheric pressure is roughly 90 bar of CO_2. Liu (2004) has modeled the proto-atmosphere of the Earth during and after the giant Moon-making impact process and has postulated that it comprised 560 bar of H_2O (twice the amount of today's oceans) and 100 bar of CO_2. The hot ~100 bar CO_2 proto-atmosphere of the Earth was also adopted by Zahnle et al. (2007) in their modeling of the Earth's early evolution after the giant impact.

After the formation of the Moon, the Earth further cooled down, Fig. 1 shows that the first drop of dense supercritical H_2O appeared (or the inception of the H_2O oceans) on the Earth when the surface temperature cooled to about 450 ± 20 °C, assuming that H_2O and CO_2 coexisted as an ideal mixture (inert to each other). Experimental and thermodynamic studies (Kennedy and Holser, 1966 and Duan et al., 1992a, b), however, show that H_2O and CO_2 are able to form supercritical H_2O-CO_2 mixtures in the temperature range between 450 and 300 °C at 660 bar. Thus, either a dense supercritical H_2O-CO_2 mixture or liquid supercritical H_2O-CO_2 mixture may precipitate to form the indigenous hot soda oceans on Earth. The inception of such H_2O-CO_2 oceans would somewhat remove CO_2 from the CO_2-dominated proto-atmosphere of the Earth. Once the indigenous oceans commenced, the proto-atmospheric pressure had to drop. "Dense" supercritical H_2O clouds might have also existed in the proto-atmosphere at high altitude, if the temperature at high altitude was cool enough. However, these cloud droplets would not be able to arrive on the surface until the surface temperature dropped below about 450 °C.

The removal of CO_2 from the Earth's proto-atmosphere was later accelerated and completed when the indigenous oceans reacted with plagioclase, the most abundant mineral on the Earth's surface, to form carbonate and clay minerals (Liu, 2004; 2023). Once CO_2 was totally removed from the proto-atmosphere, N_2 naturally becomes the most abundant component of the Earth's atmosphere as observed today.

As shown in Fig. 1, no supercritical H_2O or supercritical CO_2 was involved in the formation of the ancient Martian oceans by degassing processes. Thus, the CO_2-dominated proto-atmosphere of Mars is essentially intact.

Liu (2023) stated that the abnormality of the Earth (different atmospheric composition, possessing the oceans, the largest satellite, and the greatest average density) implies its uniqueness or rareness which, in turn, may disappoint many scientists who are interested in searching for life on other planets. As demonstrated in this study, if the proto-atmosphere of a terrestrial planet is dominated by CO_2 and if this CO_2-dominated proto-atmosphere cannot be removed due to the absence of oceans which require a large quantity of supercritical H_2O fluid at high temperatures and relatively higher atmospheric pressures, life is most likely not to be evolved on such a planet. Bio-evolution itself is a chaotic process. The progress of evolution can go in any direction and is constrained only by environments. A change of environments may modify the evolution route, create new species, or lead to total extinction. Even if one day life is found on other planets, there is no warranty that a human-like species may be evolved on that planet.

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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, Mars and Uranus and their respective atmospheric composition and surface pressure

Gases (molecular weight)	Lower Bound CM (g)	Planets	Mass (g)
		Moon (?? = ~10^{-15} bar)	7.35×10^{25}
		Mercury (O_2+Na+H_2+He = 10^{-15} bar)	3.30×10^{26}
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 (CO_2+N_2+Ar = 8×10^{-3} bar)	6.419×10^{26}
H_2O (18.02)	8.06×10^{26}		
CH_4 (16.05)	9.05×10^{26}		
He (4.00)	3.63×10^{27}		
		Venus (CO_2+N_2 = 93 bar)	4.869×10^{27}
		Earth (N_2+O_2+ Ar = 1.013 bar)	5.976×10^{27}
H_2 (2.02)	7.19×10^{27}		
		Uranus (H_2+He = ~1 bar)	8.68×10^{28}

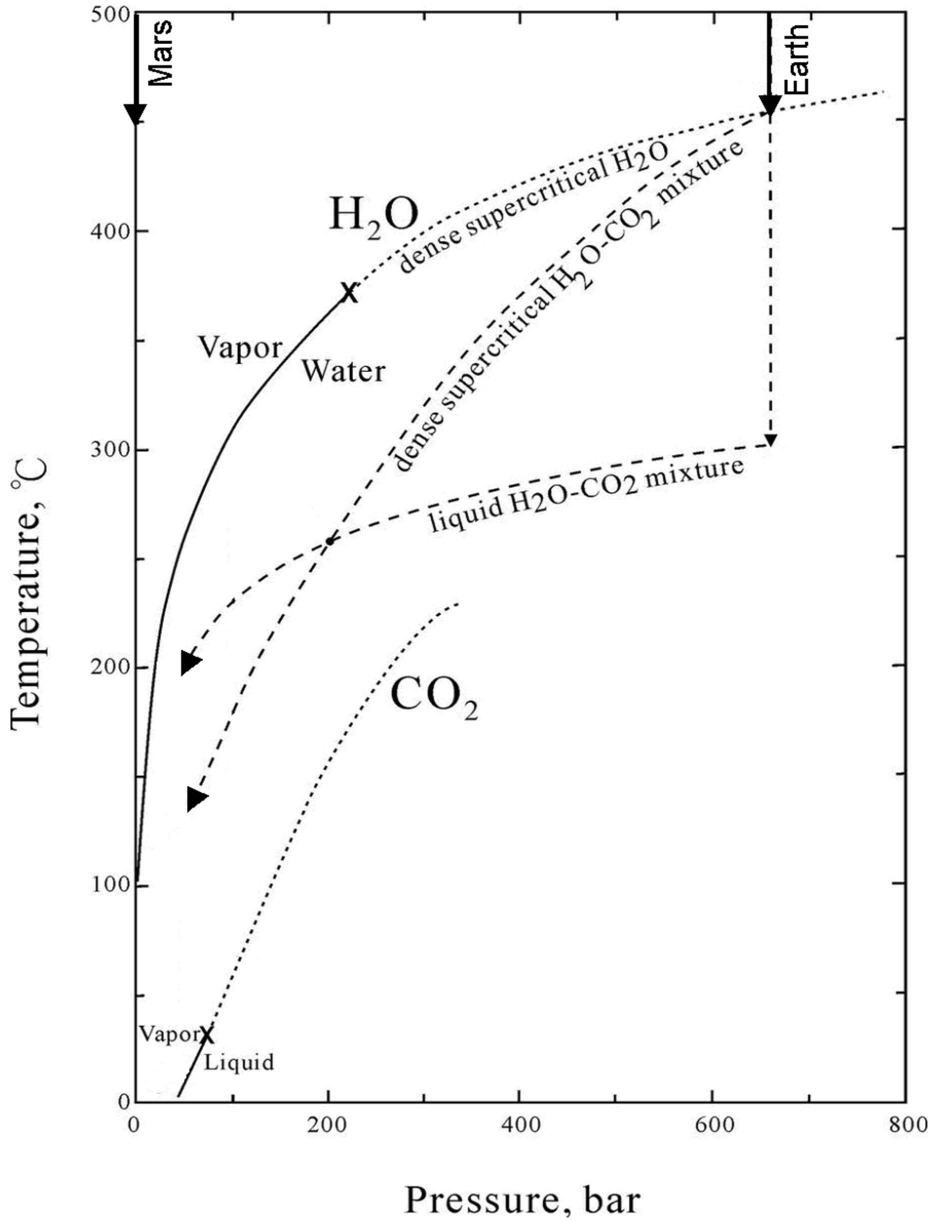

Figure 1: The vaporization temperature for both H2O and CO2 as a function of pressure (the solid curves). X marks the critical conditions of these materials. The short-dashed lines indicate the pressure-temperature conditions (beyond the critical points) at which the 'dense' supercritical H2O and CO2 exist. The long-dashed lines indicate the possible routes that dense supercritical H2O-CO2 mixture and/or liquid H2O-CO2 mixture may precipitate on the Earth's surface from its proto-atmosphere after accretion. Mars total atmospheric pressure of both H2O and CO2 right after accretion and solidification is too small to shown in the present scale (indicated by an arrow along the vertical axis). At such a low pressure, H2O and CO2 would act rather independently except possibly for forming some HCO3-. Thus, H2O degassed from Mars would condense directly to form an ocean when Mars surface cooled down below 100 oC, leaving behind CO2 in the proto-atmosphere.