American Journal of Modern Physics
2025, Vol. 14, No. 1, pp. 37-43
https://doi.org/10.11648/j.ajmp.20251401.15

Research Article

Water: The Essential Component of Our Inner Solar System

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Abstract

If our solar system started with the terrestrial planets initially covered with water, then a reasonable progression of events result in the presently observed inner solar system. Two principal assumptions have been made. One is that molten rock and the iron rich cores of the terrestrial planets can dissolve appreciable quantities of water. The other is that our solar system was formed initially from cold gas and dust which contained due to condensation large quantities of water. Water then became trapped in the cores and molten rock of the forming terrestrial planets. This in essence implies that our star formed as a lone star since if more than one star was involved it is unlikely that the gas and dust could be cold as to condense large quantities of water. Phase transitions involving water and carbon dioxide play a crucial role in the transition from this initial water covered state to what is observed today. Of the four terrestrial planets of our solar system Earth is the only one that developed mechanisms that allowed liquid water to be retained. Thus, Earth is the only terrestrial planet in our solar system that has the possibility for billion-year stability to allow evolution to work over a sufficiently long time for the evolution of intelligent life. The principal reasons for this are the presence of a magnetic field and plate tectonics that allow long term planet surface stability. The progression from an earlier state to what we see today was largely completed about 2 billion years ago so long term evolutionary development where possible should have proceeded. Mars is believed to have had surface water in this early stage but lost that as did Mercury and Venus. Volume changes upon the phase changes of water and carbon dioxide play a crucial role in driving the geology of Mars. The sublimation of carbon dioxide from solid to gas phase must play a crucial role in creating caverns and crevices below the surface if lifeforms are to exist on Mars. Simple lifeforms are then expected to exist below the surface of Mars. Recent seismic measurements indicate that both Earth and Mars possess large reservoirs of water well below the surfaces of each planet.

Keywords

Our Early Solar System, Earth, Venus, Mercury, Mars, Water in the Early Solar System

1. Introduction

If the initial state of the terrestrial planets in our solar system was to be covered by water, we want to show that a natural progression of events leads to the inner solar system that we observe today. Each terrestrial planet then has the possibility by the Drake Equation of exhibiting life of some sort. The Drake equation is a product of terms giving the probability that life may be found on a planet in the universe. Initial terms limit the probability to terrestrial planets in some sort of habitable zone in which liquid water might be found. Recently the Drake Equation was expanded to argue that Earth has a high probability to be the only site of advanced civilization in the Milky Way Galaxy. [1] This conclusion is based on the probable rarity of finding another planet that exhibits plate tectonics along with other conditions allowing liquid water. If

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Received: 3 January 2025; **Accepted:** 10 February 2025; **Published:** 24 February 2025

our solar system is examined in terms of the Drake Equation, the four terrestrial planets would be seen as possible habitable planets for life of some sort. In previous papers we have argued that Earth only acquired a sufficiently high average density to exhibit a magnetic field and plate tectonics as a result of the collision that created the Earth-Moon system. [2, 3] The Moon has sufficient mass that the rotation speed of the Earth slowly slows as the Moon moves away from Earth. The precise relationships are shown in Ref. 3. This is believed to be a possibly unique event that totally changed the future development of the Earth. In this paper we wish to further analyze our solar system to show that Earth is the only terrestrial planet that developed mechanisms for the long term retention of liquid water. Thus, Earth is the only planet in our solar system where intelligent life might have evolved. Central to this idea is the believe, as supported by the geologic record, that life slowly evolved over the last 4.5 billion years and that life was not miraculously transported to the Earth by space travel. The occasional transfer of minerals and metals between the planets is possible, but they likely would have been sterilized in the transfer. This also applies to the other terrestrial planets in our solar system in that life developed, if it existed, independently on each terrestrial planet. As a corollary, if life did start on a terrestrial planet, it could be extinguished by events peculiar to that particular planet. In this regard any events that cause liquid water to be lost from the surface of a terrestrial planet could cause the cessation of life on the surface of that planet. Our solar system appears unusual in that the terrestrial planets and the Jovian planets are widely separated. A key question then is how long liquid water needs to exist for a desired degree of evolutionary development.

Central to this paper is the hypothesis that the core and molten rock such as the mantle of a terrestrial planet can dissolve large quantities of water. It will be shown that this hypothesis can explain many factors about the terrestrial planets. The second hypothesis is that our solar system was initially formed out of gas and dust that was initially cold so that water was condensed among that gas and dust. As that gas and dust was compacted to form the terrestrial planets water was trapped in the core and molten rock. As the outer regions cooled water was precipitated to form surface water. The phase behavior of two substances, water and carbon dioxide play key roles. The expansion of water as it freezes can break rock and change surface structures. And similarly, the direct sublimation of solid carbon dioxide to vapor can cause volume expansions and near surface disruptions. The giant impact that subsequently formed the Earth-Moon system occurred about 20 to 100 million years after the Sun had started to radiate energy. [4] The debris that then subsequently coalesced to form the Moon was well within any frost line so that the Moon condensed out of dry material and is said to be dry. Two recent discoveries that support this hypothesis are an experiment showing the condensation of water following the condensing of molten lava. [5] And the discovery of steam shoudered planets by the James Webb Space Telescope [6]. A recent paper has also supported this hypothesis. [7] Underground water has also been reported. [8] Water in this scenario is far more prevalent than usually thought. It is only liquid surface water that is rare in the solar system. Usually it has been assumed that these hot forming planets were devoid of water and that water had to be brought to the surfaces by some hypothesized method such as comet impacts, or that water condensed onto colder asteroids from the asteroid belt was somehow returned to the Earth. Little consideration was given as to how water dissolved in molten rock and cores applied to the terrestrial planets other than Earth.

2. Results and Discussion

In a previous paper it has been shown that to a very good approximation the four terrestrial planets move about the center of the Sun, but that the Sun and system of Jovian planets move about a collective center of mass point. [9] The long term stability of the terrestrial planets in our solar system is believed to be a defining characterization of our solar system. The terrestrial planets then developed largely independent of each other so that separate formation statistics can be scaled between the terrestrial planets. The Sun at its formation rapidly came to a luminosity of about 0.7 times the present value and that value has been rising approximately linearly ever since. [10, 11]. Table 1 shows the orbital parameters of the terrestrial planets and their expected surface temperatures shortly after formation in degrees centigrade and in Kelvin units without considering any atmospheric effects. These values were calculated using Equation 1 with a luminosity of 0.7 times the present Sun luminosity as appropriate for the early Sun.

$$L \ \frac{\pi R_P{}^2}{4\pi D^2} = 4\pi R_P{}^2 \sigma T^4 \qquad (1)$$

In this energy balance equation L is the Sun's luminosity, R_P = the planet radius, D the Sun to Planet distance, T the planet surface temperature and σ the Stefan-Boltzmann constant.

Table 1. *Surface Temperatures in the early Solar System when the Sun's Luminosity equaled to 0.7 times the present Sun Luminosity. The orbital properties are NASA Planetary Tables.*

	Mercury	Venus	Earth	Mars
Distance From Sun (m)	0.579E11	1.082E11	1.496E11	2.279E11

	Mercury	Venus	Earth	Mars
Perihelion (m)	0.460E11	1.075E11	1.471E11	2.067E11
Aphelion (m)	0.698E11	1.089E11	1.521E11	2.493E11
Eccentricity	0.206	0.007	0.017	0.094
Obliquity to Orbit (degrees)	0.034	177.4	23.4	25.2
Surface Temperature Without Atmospheric Effects (K)	409	299	255	206
Surface Temp. (°C)	136	26	-18	-67
Planet Radius (m) =	2.44E+6	6.05E+6	6.38E+6	3.39E+6
Energy/(energy radiated/second) (time units)	1.00E+0	8.66E+0	1.75E+1	2.16E+1
Fractional Energy lost per second proportional	17.5	2.02	1.00	0.81
Planet Magntosphere	Yes, = HE/100	No	Yes, = HE	No

In Table 1 even Mercury has been taken to be initially water covered but the surface temperature indicates that initial conditions were above the critical point of water, 374 deg. C. This same equation is not usually applied to Mercury after it has lost its atmosphere. The energy contained within a planet is proportional to the volume as R^3 while the energy radiated is proportional to the surface area times temperature raised to the fourth power. The energy contained divided by the rate of energy radiated then gives a natural relative time unit for planet evolution as a function of percentage of energy lost. Table 1 also gives the relative time unit for planet evolution which shows that the change unit for the planet Mercury is nearly ten times shorter than that for Venus and nearly 18 times shorter than that for the Earth. If one considers the reciprocal of this characteristic time then one has the time period for a given amount of energy change. Thus Mercury, can be seen as being smaller and hotter to have a faster rate of change than a larger and cooler planet. The second to last row in Table 1 then gives the rate of energy change relative to that of the Earth. The last row in the table indicates that Venus and Mars never developed magnetic fields, but that Earth and Mercury did with the magnetic field of Mercury presently only being about 1/100 that of the Earth.

It should be noted that atmospheric effects always result in a warming effect over a planet without an atmosphere. This is shown by Equation 2 where the planet surface albedo is represented by "a" and "τ" represents an atmospheric infrared absorption and reradiation parameter. Tau, τ, is often called the optical depth. At the present time, for example, atmospheric greenhouse gas effects raise the average present surface of the Earth from below the freezing point of water to about 16 ℃ above the freezing point of water. This value is expected from Equation 2 with the Sun's present luminosity and a value of $\tau \approx 1$ with an albedo value of 0.3 as usually used for the present Earth.

$$L \frac{\pi {R_P}^2}{4\pi D^2}(1-a)(1+\tau) = 4\pi {R_P}^2 \sigma T^4 \qquad (2)$$

Here we have started with the condition that Venus, Earth, Mars, and even Mercury, started with a covering of water in the early solar system. This watery surface is expected if it is assumed that hot molten rock can dissolve large quantities of water which is precipitated as the crustal regions cool. This is consistent with the Moon being dry and water free since the Moon formed as a collection of scattered and separated debris which exposed that debris to cooling and drying action of the enhanced surface area of the debris. The collision that created the Earth-Moon system occurred after the Sun had started to radiate energy. It should be noted that this initial watery surface is what would be called salt water. Fresh water has to be made by an evaporation process that separates freshwater from the ubiquitous saltwater. Surface disruptions creating higher altitude surface regions are needed due to volcanic action and or early planetary collisions are needed to provide condensation regions for the collection of fresh water. For Earth the time needed to get land poking above the salt water is about 500 million years as indicated by the time at the end of the Hadean Period. [12] This time can statistically be scaled by the time factors of Table 1 to indicate a required time for the appearance of fresh water of about 500/18 million years for Mercury due its small size and high temperature, 500/2 million years for Venus, and 500/0.8 million years for Mars principally due to its lower surface temperature. The cores and mantle of all these terrestrial planets continue molten and geologically active at this stage and this geological activity continues to this day. The Earth and Mercury manifest magnetic fields but Venus and Mars do not. This is consistent with the hypothesis reached in a previous paper that an average density greater than 5350 ± 50 kg/m^3 is required for a terrestrial planet to exhibit a magnetic field. [2]

There is then the expectation that the surface of Mercury should be covered with many salts that had been dissolved in that hot water ocean. It should be noted that the initial surface temperature is above the critical point of water so that there is no apparent volume change as water leaves the surface. Such elements are expected to include sodium, aluminum, magnesium, sulfur, calcium and other light elements. These are just the elements that the Messenger mission found to be abundant on the surface of Mercury. [13] The large eccentricity of Mercury's orbit is assumed to be due to impacts during its formation which resulted in a nonspherical mass distribution. The nonspherical mass regions of Mercury coupled with the eccentric orbit of Mercury resulted in a 3:2 spin-orbit resonance so that Mercury rotates 3 times on its axis for every two revolutions about the Sun. There are then no regions about the equatorial region that are shaded for longer than multiple year periods of time. The low obliquity of Mercury as given in Table 1 indicates that polar depressions can be perpetually shaded. The low thermal conductivity of rocky polar regions implies that ice can stay frozen in polar depressions. As molten mantle regions cool water is expected to be precipitated with shrinkage contractions appearing in the crust. Water vapor should be present near the surface but the surface would be above the critical point for liquid water to persist on the surface. Water vapor has unexpectantly been found to be present in the atmosphere of Mercury. [13]

Mercury has a relatively small magnetic field compared to that of Earth so that surface water above the critical point is lost without transitioning to a true liquid state. This is a one-way process so that there is no net accumulation of water onto the surface of Mercury. Statistically to get a rumpled surface corresponding to the Hadean Period of the Earth would take a time of 500/18 million years. Light elements are also ejected by the solar wind which acts to concentrate these at the surface. This also acts to decrease the crustal radius and to make the core radius to planet radius a larger fraction than that for the other terrestrial planets. For Mercury to initially have a water covered surface then it would have an atmosphere of mostly water vapor. This hot boiling water surface with water above the critical point of water would place Mercury interior to any Goldilocks zone where water conducive to life processes is expected to be found. Once water and hence the atmosphere is lost from Mercury then the side facing the Sun becomes very hot and the opposite side very cold. The rotation axis of Mercury is tilted at nominally 0 °from the orbital axis so that depressions near the poles can be perpetually shaded and hold water ice deposits. [13] Mercury is sufficiently hot that ice doesn't form either on the surface or in the atmosphere as snow. This means that there is no floating of ice deposits as promotes life processes on the Earth, or potentially on other planets such as Venus, Earth, and Mars.

It has already been stated that the observed opposite rotation of Venus resulted from an interaction of the relatively high magnetic field of the Sun at formation with the electrically conducting core of Venus. [2] It should be noted that since the interaction between Venus and the Sun depends on the electrical conductivity of the core of Venus and not the magnetic properties of the core of Venus the interaction results in the same rotation of Venus even as the polarity of the Sun's magnetic field reverses. This would not be true if the interaction depended upon any magnetic properties of the core of Venus. Since the Sun's magnetic field was only strong enough for this during the initial formation of the Sun then the core of Venus must have been nonmagnetic in the early history of Venus. This says that Venus never developed a magnetosphere rather than losing a magnetic field after a certain period of time. This would also suggest that Mars developed similarly so that Mars never developed a global magnetic field rather than at first having a magnetic field and then losing that field after a certain length of time.

If the similarly sized planets of Venus and Earth are considered the vapor pressure of water versus temperature plays an important role. This is a highly nonlinear function with Venus starting at an initial temperature of ≈300 K and Earth at 255 K. Over a certain time period the atmosphere of Venus changes from water vapor to one of mostly carbon dioxide. There is no plateauing of this water loss so that the atmosphere of Venus becomes devoid of hydrogen and hence of water. Venus does not have a magnetic field so that the solar wind also acts to knock away hydrogen and other light elements. The timescale for this conversion of the atmosphere corresponds up to what is called the Great Oxidation Event of the Earth and due to the elevated temperatures should be approximately 2100/2 million years. The relative time factor from Table 1 has been used here. This is due to photodissociation of water in the upper atmosphere and hydrogen then being lost to space. Venus currently has very little water left and may be considered very dry. Since carbon dioxide is a greenhouse gas by Equation 2 the atmospheric absorption factor changes from a low value of Tau to at least a value of 70, the currently accepted value for Venus at the present time. Due to the highly reflective clouds of Venus the surface albedo of Venus is about 0.77. The present surface temperature of Venus is then 743 K by Equation 2. The water loss process is continuous without any reversals or plateauing. Conditions on Venus then become more and more hostile to life as we know it. Venus never developed a magnetic field and therefore also does not exhibit plate tectonics as a means of gradually releasing interior heat. The Venus surface was last resurfaced most recently about 300 million years ago. [14] Such a short time period over which the surface is resurfaced does not allow sufficient time for evolutionary development of what could be described as complex or intelligent lifeforms.

Due to the lower initial temperature of Earth and the nonlinearity of the vapor pressure of water from Table 1, a much lower fraction of water is disassociated by sunlight in the upper atmosphere of the young Earth. A much greater length of time must then pass so oxygen produced by algae then has time to reach the upper atmosphere where it can combine with dissociated H to make heavier water molecules which are lost to space at a much lower rate than hydrogen molecules. It is usually thought that the Great Oxidation Event occurred about 2.4 billion years ago. [15] Earth then exhibited an environment with both salt and freshwater which allowed long term evolution to advance over billion-year timescales. Following the Great Oxidation Event, ≈2.1 billion years from the start of the solar system, Earth has conditions to stabilize the amount of surface water that can then be characterized as principally liquid water and ice. Recent seismic measurements have shown there exists at the top of the lower mantle at a depth of about 710 km large quantities of water. [8]

Continuing out from the Sun, Mars is encountered that from an initial water covering eventually loses that water covering for a number of reasons. Due to its greater distance from the Sun Mars exhibited a lower temperature and easier route to change because of its smaller size. The combination of a lower temperature and smaller size give a relative time scale factor that changes are expected to change slower than that of the Earth. The corresponding time period to get a varied elevated surface features corresponding to the Hadean Period of the Earth would then be about 500/0.8 million years. To get the majority of the surface water removed is estimated to correspond to the Oxidation Event of the Earth corresponding to about 2100/0.8 million years. The current gas in the Martian atmosphere is carbon dioxide. The triple point for carbon dioxide is -56.57 ℃ and 5.11 Atm of pressure so carbon dioxide near the surface of Mars sublimates directly from a solid phase to the gas phase. Mars without a magnetic field has nothing to prevent the solar wind from stripping away atoms from the atmosphere. Similarly solar radiation and solar wind particles would make subsurface or some other shielding necessary for lifeforms to become established. Over long periods of time as the edges of the core cooled interior water dissolved in the core would be released to make its way to the surface. It is then entirely reasonable that sporadically water would gush to the surface. But the low surface pressure would mean that water would have a short lifetime on the surface. To have stable liquid water on the surface of Mars temperatures and pressure must be above the triple point of water. The triple point of water is 273.16 K = 0.01 ℃ and a pressure of 0.0060 atm. Considering a point in time corresponding to about the end of the Hadean Period on Earth the Sun's luminosity would be about 0.8 times the present Sun's value. An albedo of 0.3 is very reasonable for a rocky planet. Equation 2 can then be used to plot surface temperature versus tau for Mars at this time as shown in Figure 1. A value of tau of at least 3 to 7 is then needed to raise the surface temperature above the triple point of water. A Martian atmosphere of water vapor, carbon dioxide, and some pressure enhancing gas such as nitrogen is then needed to raise the pressure and also increase Tau to at least be in the range from 3 to 7. The polyatomic gases water vapor and carbon dioxide are both greenhouse gases while the diatomic nitrogen gas can provide most of the pressure. Similarly on Earth the diatomic gases nitrogen and oxygen together with monatomic argon provide most of the atmospheric pressure. The critical point pressure for water is 0.006 Atm. which is currently the surface pressure on Mars. Liquid water thus cannot form currently in the atmosphere of Mars at the present time. As the solar wind removes for example nitrogen from the atmosphere of Mars then the stability of surface water on Mars is lost. The stripping of nitrogen from the atmosphere of Mars is expected to take 2100/0.8 million years. There is no process that can restore the surface pressure of Mars so the loss of surface water is a one way process. Liquid water can then only be stable below the surface where the pressures are higher. Again in the case of Mars recent seismic measurements have indicated the presence of large quantities of water at a depth of 11.5 to 20 km below the surface. [16] Trapped solid carbon dioxide sublimating to a gas phase can then provide high enough pressures below the surface to make liquid water stable in caverns or crevices. Since the surface of Mars then became relatively dry about 2 billion years ago ample time has passed that lifeforms of some sort should have been established in such underground water deposits. A recent study has argued that habitable conditions on Mars could date back to 3.9 billion years ago.

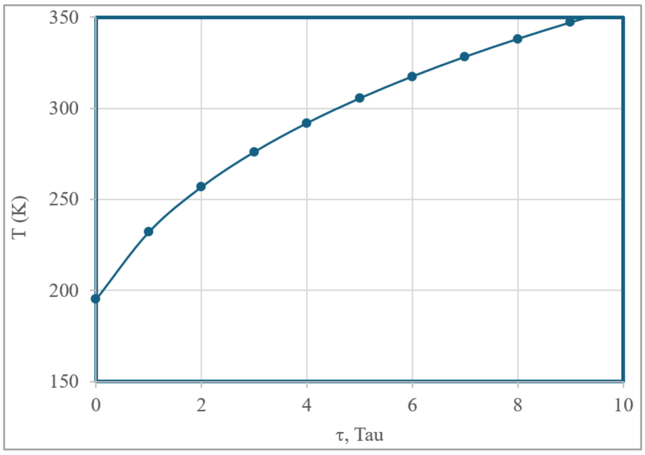

Figure 1. The surface temperature of Mars in the early solar system is plotted versus the Tau value.

3. Conclusions

Two principal assumptions have been made. One is that molten rock and the iron rich cores of the terrestrial planets can dissolve appreciable quantities of water. In this regard seismic measurements indicate that both Earth and Mars indicate that each of these planets contain large reservoirs of water located well the surfaces of each planet. The other is that our solar system was formed initially from cold gas and dust which contained due to condensation large quantities of water. This says that the frost line for our inner planets was interior to the terrestrial planets. Water then became trapped in the cores and molten rock of the forming terrestrial planets. Mercury, Venus, and Mars lost this surface water. Seismic measurements have indicated that both Earth and Mars have large amounts of water located well below the surfaces of each planet. Surface water was lost by routes particular to the individual planet approximately 2 billion years ago. The phase diagrams of water and carbon dioxide play a crucial role in whether water is retained or lost. This in essence implies that our star formed as a lone star since if more than one star was involved it is unlikely that the gas and dust could be cold as to condense large quantities of water. Other similar mass stars could be formed in multiple star systems that would not contain initially large quantities of water that would not correspond to our solar system.

This assumption has implications for each of the terrestrial planets in our solar system. First off is the implication that the four terrestrial planets developed independently of each other. For Mercury there is the implication that the surface be rich in salt related elements that were originally dissolved in the initial salt water. The surface temperatures of Mercury are above the critical temperature of water so there is no volume step as water expands from liquid to gas. Second is the expectation that there should be shrinkage quakes as water is released from the outer mantle in episodic quakes. And third water vapor should be present near the surface of the hot surface of Mercury. Mercury should also have a magnetic field.

For Venus the initially relatively high surface temperature together with the nonlinear vapor pressure curve of water would imply that relatively large amounts of water vapor reached the upper atmosphere where it could be photo-dissociated by sunlight. Hydrogen would then be lost to space so that surface regions are then devoid of water. The oxygen can then become bound as carbon dioxide so that the infrared absorption, the Tau value, increases and the surface temperature increases. Due to the higher surface temperatures geologic features evolve about twice as fast as on the Earth as shown in Table 1. Since Venus exhibits neither a magnetic field nor plate tectonics long term energy loss must proceed via convulsive events with the surface being remade after time periods too short for the evolutionary development of complex life forms let alone intelligent life forms.

Earth is distinguished by several unique features that act to preserve and protect surface water. One is that the initial temperatures as shown in Table 1 is sufficiently low that the vapor pressure of water is sufficiently low that comparatively little water as compared to Venus reaches the upper atmosphere. The magnetic field of the Earth limits the action of the solar wind from stripping water and the outer atmosphere away from the Earth. Plate tectonics accompanying the magnetic field allows for a gradual release of internal heat so that surface convulsions do not occur. Over long periods of time as algae release oxygen, the Oxidation Event, other molecules are then in the upper atmosphere that act to retain photo dissociated hydrogen from escaping from the Earth. There is then a net loss of water from the Earth to space up to the Oxidation Event that occurred about 2.4 billion years ago. Thus, the plate tectonic system of Earth acts to preserve water over billions of years. Only then is stability over billions of years possible for the evolutionary development of intelligent technologically capable life forms. Early on some of the photo dissociated oxygen combines with carbon which makes carbon dioxide, a greenhouse gas, that then acts to raise the surface temperature of the Earth. Thus, through this process surface water is protected as the surface temperature is raised from below to above the freezing point of water.

Mars without a magnetic field has nothing to prevent the solar wind from stripping away atoms from the atmosphere. Over long periods of time as the edges of the core cooled interior water dissolved in the core would be released to make its way to the surface. It is then entirely reasonable that from time-to-time water would gush to the surface. But the low surface pressure would mean that water would have a short lifetime on the surface. To have stable liquid water on the surface of Mars temperatures and pressure must be above the triple point of water. The triple point of water is 273.16 K = 0.01 ℃ and a pressure of 0.0060 atm. Considering a point in time corresponding to about the end of the Hadean Period on Earth the Sun's luminosity would be about 0.8 times the present Sun's value. An albedo of 0.3 is very reasonable for a rocky planet. Equation 2 has then been used to plot surface temperature versus Tau for Mars at this time as shown in Figure 1. A value of tau of at least 3 to 7 is then needed to raise the surface temperature above the triple point of water. As the solar wind gradually knocks surface atoms away from the surface the Tau value falls and liquid water was no longer stable on the Martian surface. It is doubtful that liquid water could have been stable on Mars for up to a billion years. The surface temperature would fall to low enough values to freeze carbon dioxide as presently observed at the poles of Mars during the winter seasons. Two substances, water and carbon dioxide, act to influence the surface of Mars. In caverns and crevices below the surface carbon dioxide can sublimate to increase the pressure so that liquid water can be stable in such caverns. Mars, without either a magnetic field nor plate tectonics provides limited periods of stability for the evolution of water bearing strata either below the surface or on the surface of the planet. Simple lifeforms are then expected to exist below the surface to afford radiation and solar wind protection.

Consistent with the original hypothesis that molten rock and lava can dissolve large quantities of water, seismic measurements have shown that both Earth and Mars exhibit large reservoirs of water well the surfaces of each of these planets. Starting from a state in which each terrestrial planet was covered by water each planet has independently been shown to have a path to advance to their presently observed appearance.

Author Contributions

Fred John Cadieu is the sole author. The author read and approved the final manuscript.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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