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Radial migration and dehydration of phyllosilicates in the solar nebula

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Abstract

While it is currently thought that Earth's water was delivered by hydrous minerals, the origin of these minerals is still debated. Nebular models suggest that the area where the Earth formed was too hot for these minerals to form, leading many to believe that they were delivered by large planetary embryos which formed in the outer asteroid belt region of the solar nebula. Others have argued that the hydrous minerals were present during the early accretion phase of the Earth in order to explain different aspects of its geochemistry and therefore, must have formed locally, implying that the nebula must have been cooler than the models predict. In this paper we explore a new possibility: that these hydrous minerals were formed in the outer asteroid belt region of the solar nebula and were then brought into the hotter regions of the nebula by gas drag where they were incorporated into the planetesimals which formed there. The hydrated minerals were able to survive for long periods of time in this hot region due to the sluggish dehydration kinetics. We find that this process need not have been efficient, requiring only a small amount (~few percentages) of the material in the outer asteroid belt region of the nebula to be subject to this process. This delivery mechanism provides a way for hydrous minerals to be incorporated early on into the planetesimals which were accreted by the Earth without having to alter the generally accepted solar nebula models that are consistent with meteoritic and asteroidal observations.

Keywords: solar nebula; meteorites; water; planet formation

1. Introduction

The presence of water on Earth has puzzled planetary scientists for some time. Standard models for the solar nebula–the cloud of gas and dust from which our solar system formed–suggest that the area where the Earth formed would have been too hot to

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allow water to be incorporated into solids. In fact, it has been shown that because water would condense only in the cooler outer regions of the nebula, diffusion would cause the water vapor to migrate outwards beyond the snow line where it would condense, essentially dehydrating the inner nebula on relatively short timescales (~10^{5-6} yrs) [1–3]. This would be true even beyond the orbit of Earth, making the evidence for large amounts of water on a young Mars equally puzzling.

If water was not able to be incorporated into solids at the location where the Earth formed, it must have been carried inward on bodies from the outer nebula. Comets were long considered as a possible source, not only because of their high water content, but also because they are rich in organic material, allowing one or more cometary impacts to not only deliver large amounts of water to the young Earth, but also seed it with the necessary organics from which life would have developed. However, the inferred D/H ratios in recently observed comets are higher than that found in Earth's oceans [4]. If these ratios are representative of the ratios of comets 4.5 billion years ago (an untested assumption), then it is difficult to understand how the D/H ratio would have decreased over time to its current value. In addition, the impact of a comet with the young Earth would be an improbable event, and in order to provide Earth with enough water, there must have been a much larger population of objects in the Kuiper Belt than currently considered likely [5].

Carbonaceous chondrites are the only water-rich, extraterrestrial objects currently observed in the solar system with D/H ratios similar to the Earth's [4]. This has led to the consideration that volatile-rich, rocky planetesimals or planetary embryos (either composed of carbonaceous chondrite material or simply containing hydrated minerals) could have provided the Earth with its water inventory. How and when these objects formed and were then delivered to Earth remains to be determined. Possibilities include the dynamical scattering of hydrated embryos from the outer asteroid belt [6] or the local formation hydrated minerals in a nebula much cooler than previously thought [7]. Discriminating between these possibilities requires a more detailed examination of the chondritic meteorites and their parent bodies.

Carbonaceous chondrites are among the most primitive objects in the solar system and are thought to record a history of the processes which occurred in the solar nebula. A subset of these meteorites, the CI, CM, and CR chondrites, are rich in hydrous minerals, implying that they formed in a region where water could interact with solid materials. Evidence for other primitive hydrated bodies is seen in the modern-day outer asteroid belt and the Jupiter Trojan asteroid population which are dominated by P-, D-, and T-type asteroids [8]. The spectra of some of these objects indicate organic and phyllosilicate-rich surfaces [9]. While others do not demonstrate spectral evidence for hydration, such features may be masked by the presence of carbon-bearing materials [10]. In fact, it has been suggested that the Trojan asteroid 624 Hektor, despite having no 3-μm absorption band in its spectrum, could contain up to 40% phyllosilicates. In addition, the Tagish Lake meteorite is considered to be a possible sample of a D-type asteroid, and it contains evidence of its parent body having been exposed to large amounts of water [11]. Thus, the outer asteroid belt (outside ~2.5 AU) may have been abundant in objects that contain water-bearing minerals. There is little evidence that meteorites from inside this distance contain much in the way of hydrated minerals [12].

In order for the Earth to acquire its water inventory, which is estimated to be on the order of $5\times10^{-4}\ M_{\oplus}$, it would therefore have had to accrete material which formed at a distance outside of 2.5 AU. The water in hydrated carbonaceous chondrites is generally locked up in phyllosilicate minerals, with the water content making up roughly 10 wt.% of the meteorites. Thus, approximately $5\times10^{-3}\ M_{\oplus}$ worth of hydrated carbonaceous material would have had to been brought to 1 AU in order for the Earth to accrete its current water content. In modeling the redistribution of planetary embryos in the early solar system, it was shown that the observed D/H ratio for the Earth can be achieved by having it accrete several carbonaceous-type embryos from the outer asteroid belt [6]. These bodies would have been scattered inward from the outer belt, and accreted at random times throughout the course of the Earth's growth, but this is limited to the time after large bodies formed in the asteroid belt.

In contrast to this model is the argument that the water-bearing phases accreted by the Earth formed at 1

AU and that the Earth accreted from planetesimals that contained such minerals [7,13]. This model is generally favored by geochemists who argue that the presence of water during the very early accretion of the Earth would explain the elemental partitioning between silicates and metals during differentiation and would provide an opaque atmosphere which would help maintain the Earth's magma ocean at its surface [13].

While this latter scenario is appealing for geochemical reasons, it requires the nebula to have been much cooler than generally accepted in order for hydrous minerals to form at 1 AU. In addition, this scenario seems to contradict the observation and meteoritic evidence that the asteroids that formed inside of 2.5 AU are almost totally anhydrous while those outside of it are hydrous [8,12]. Thus, the dynamical history of water delivery may be inconsistent with the geochemical interpretation of when water was delivered to the inner solar system. As a way of addressing this, we propose a new scenario by which the Earth accreted its water which builds on the strengths of these two leading theories. That is, we propose that hydrous minerals formed in the outer asteroid belt region of the solar nebula as in the distal model of [6], but were brought in to the inner nebula and survived the high-temperature environment where they were accreted by planetesimals at 1 AU. Bringing this material inward at a steady (rather than random) manner and at an early time would provide a way to have hydrous minerals present at the beginning stages of the Earth's formation, as seems to be required by the chemistry of the Earth [7,13].

In the next section we discuss the possible ways that the hydrous minerals found in carbonaceous meteorites could have formed, with particular interest paid to the timescales needed for their formation. In Section 3, we discuss the migration and dehydration of these minerals after they formed in the outer asteroid belt region of the solar nebula. In Section 4 we discuss the implications of these considerations for the delivery of water to the terrestrial planets.

2. Phyllosilicates in the solar nebula

While phyllosilicates are thought to be thermodynamically stable under solar nebula conditions at temperatures below ~250 K, it has been suggested that their formation via gas-solid reactions would be too slow to allow them to form on nebular timescales [14]. This required that most of these hydrous minerals formed via aqueous alteration processes on the meteorite parent body through the melting of ice that accreted with the body and the subsequent reaction of the resulting water with the anhydrous rock. If aqueous alteration was the sole mechanism responsible for the formation of hydrated silicates in the early solar system, it has not been shown whether it would occur prior to removal of the solar nebula or after. Studies have shown that the formation of serpentine (a type of phyllosilicate) such as that found in CM chondrites could be achieved through the aqueous alteration process provided that the parent body accreted less than 4 Ma after the collapse of the solar nebula [15]. Later formation would not allow the interior temperature of the parent body to get high enough to melt ice due to most of the short-lived radionuclides then being extinct. Thus, if meteoritic serpentine can only form on timescales less than 4 Ma, it is possible, if not probable, that it formed before the nebular gas was removed, which could have taken as long as 10 Myr [16,17]. In fact, such long lifetimes for the nebula may be required in order to form the giant planets if they formed via the core accretion mechanism [18].

While parent body formation of phyllosilicates has been the prevailing theory for many years, it has recently been argued that the fine-grained phyllosilicates found in the rims around chondrules in the CM chondrite could have formed in shock waves operating in icy regions of the solar nebula [19]. Larger grains, such as those found in the matrix of these meteorites, could also form in such an environment if the gas–solid hydration was only slightly faster than originally suggested. In fact, based on the dehydration kinetics of talc [20], it has been suggested that the activation energy originally used to determine the formation rate of phyllosilicates was too high [21]. Due to the exponential dependence of kinetic reactions on activation energy, a smaller activation energy would lead to much faster reaction kinetics. Thus, it is possible that grains micrometers in size could be hydrated within the solar nebula, which would then be available to accrete into larger bodies. This would allow large amounts of hydrated material to form within the solar nebula at a given time, and then be accreted into larger bodies.

If phyllosilicate-bearing bodies were present in the solar nebula, their orbits would evolve over time due to a variety of effects. The most significant effect would likely be inward migration due to gas drag since it operates on very short timescales. Because the solar nebula is expected to have a radial pressure gradient, the nebular gas would orbit the sun at velocity below the Keplerian velocity. As solid bodies attempted to follow Keplerian orbits, they would experience a headwind which would cause them to migrate inwards at a rate that can be calculated as using the equations derived in previous work [22]. As these bodies moved inwards, the nebular environment in which they were surrounded would get hotter, causing some of the water contained within them to escape. If the rate at which this took place was slow, then phyllosilicates could have migrated very far inward while still retaining their water.

The rate at which these phyllosilicate-bearing bodies would migrate inwards would depend strongly on their sizes, with the fastest migrators being those roughly 1 m in size [22]. Carbonaceous type bodies of this size could have been created in a number of ways. If phyllosilicates were the result of nebular processes, then, as these small particles coagulated and then accreted, they would eventually wind up in bodies of this size. For those phyllosilicates which formed by aqueous alteration processes on a parent body, that body likely experienced a number of collisions after it formed and therefore could have ejected material in a range of sizes. Models of planetesimal growth in the solar nebula which account for both accretion and collisional destruction show that a range of sizes from 1 μm to 10 km can exist in a given location at a given time [23,24]. Thus, phyllosilicates likely were contained in many different sized bodies throughout the first few million years after they formed.

3. Migration and dehydration of phyllosilicates

As a solid body migrates inward, it will be exposed to hotter temperatures and chemical environments that are different than the region where the body formed. This effect was used to look at the vaporization of bodies composed of water ice, and it was found that such solids would not survive migrating all the way to 1 AU in order to be incorporated into the planetesimals that formed there [2,3,25]. This is because the vaporization of ice begins when temperatures are above its condensation temperature (~160 K) and occurs on timescales short compared to the migration time of the bodies.

In the case of phyllosilicates, they are expected to form in the nebula at temperatures below ~225 K [14]. However, studies of phyllosilicates in carbonaceous chondrites have shown that the minerals will not begin to decompose until they reach temperatures of 600–700 K [26]. This is likely due, in part, to the high activation energy required to initiate decomposition of phyllosilicates, which for chrysotile (a phyllosilicate which is common in carbonaceous chondrites) has been measured to be between 300 and 600 kJ/mol [27,20].

This means that phyllosilicates can migrate inwards to distances where temperatures are at this level before dehydration would occur. Where this would occur would depend on nebular parameters, but would likely be at or inside 1 AU for most of the lifetime of the nebula. Fig. 1 shows the midplane temperature profile of the nebula as a function of distance for three different models. The nebula is

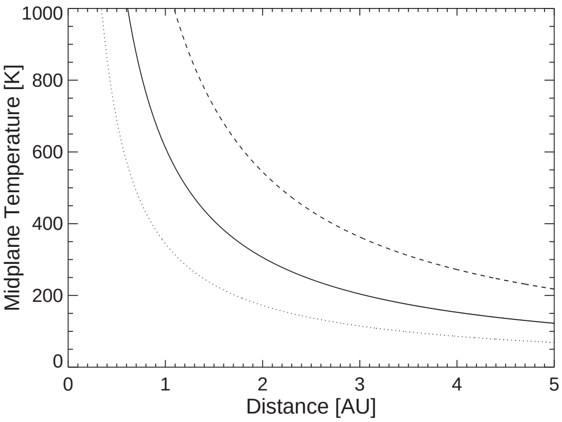

Fig. 1. Plotted are the midplane temperatures expected in a minimum mass nebula for three different mass accretion rates onto the sun (from top to bottom): 10^{-7}, 10^{-8}, and 10^{-9} $\dot{M}_{\odot}$/yr. The latter rates are likely more appropriate for a minimum mass nebula, and provide a thermal profile which easily allows for the transport and survival of hydrous minerals from 5 AU to 1 AU.

assumed to have a surface density profile that is close to a minimum mass that goes as [3]:

$$\Sigma(r) = 1700\left(\frac{r}{1\mathrm{AU}}\right)^{-1} \mathrm{g\ cm}^{-2} \qquad (1)$$

To calculate the temperature of the nebula, a mass accretion rate onto the sun, $\dot{M}_{\odot}$, is assumed and used in the formula given by [28]:

$$T_{\mathrm{m}}^{4} = \frac{3\tau}{64\pi\sigma}\frac{GM_{\odot}\dot{M}_{\odot}}{r^{3}} \qquad (2)$$

In this equation, σ is the Stefan–Boltzmann constant, G is the gravitational constant, $M_{\odot}$ is the mass of the sun, and 1/2 is the optical depth from the nebular midplane to the disk surface. The optical depth is given by $\kappa\Sigma/2$, where κ is the opacity of the nebula (assumed to be 5 $\mathrm{cm}^2\ \mathrm{g}^{-1}$ [28]).

The three mass accretion rates used in Fig. 1 are 10^{-7}, 10^{-8}, and 10^{-9} $M_{\odot}$/yr. For a minimum mass nebula, a value of 10^{-7} is likely to be greater than expected, as such high mass accretion rates are thought to occur only during the early, more massive stages of evolution. A value of 10^{-8} $M_{\odot}$/yr is typical of T-Tauri stars 10^6 yrs old [29]. As discussed above, the timing of phyllosilicate formation is uncertain, though because most carbonaceous chondrites contain chondrules, phyllosilicate-bearing bodies likely were built at least up to 2–3 Myr after the formation of the solar nebula [30], if not later. Thus, mass accretion rates between 10^{-9} and 10^{-8} $M_{\odot}$/yr are reasonable.

Fig. 2 shows the same results as Fig. 1, but focusing on the temperature structure around 1 AU for the models presented. Once the nebula mass accretion rate reached ~10^{-8} $M_{\odot}$/yr, the nebular midplane temperature would be just over 600 K. Thus, phyllosilicate-bearing bodies carried here would likely be able to be incorporated into planetesimals without losing significant amounts of water. Only at higher nebular mass accretion rates, when temperatures are at much higher values at 1 AU, would this be a problem. By examining different nebula conditions we found that phyllosilicates can travel and survive the greatest distances if the nebula is low in mass, the accretion rate onto the sun is low, or the opacity of the nebula is low as would be expected as fine-grained dust is accreted into larger bodies [31]. All of these conditions would likely be met at the later stages of nebular evolution as the gas begins to dissipate and large solids are formed. This means phyllosilicate transport would be most efficient a few million years after the collapse of the solar nebula, providing enough time for the hydrated minerals to form.

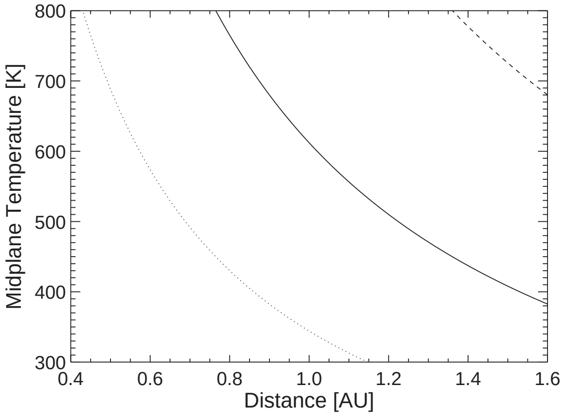

Fig. 2. Same as Fig. 1, but focusing on the temperatures at 1 AU. Phyllosilicates such as those found in primitive meteorites would likely begin to decompose at temperatures between 600 and 700 K, which is above the values predicted 10^6 years after the formation of the solar system when volatile-rich bodies such as the carbonaceous chondrites are being formed.

4. Can this explain Earth's water?

Estimates of Earth's total water content vary over a range of values, but a total of 5×10^{-4} $M_{\oplus}$ is a roughly typical estimate [6]. If carbonaceous material is 10 wt.% water, that means 5×10^{-3} $M_{\oplus}$ worth of this material must be delivered to the Earth feeding zone (~1 AU) without any significant dehydration occurring if it was the lone source of water. As carbonaceous material was delivered to this region, it could be incorporated into large planetesimals and stored until the Earth accreted. How much water would be retained during the outgassing and growth of the Earth is uncertain and requires further study, but if 50% of the water is retained by the Earth after accretion, that means roughly 1% of Earth's mass (roughly a lunar mass) must be delivered from the carbonaceous chondrite source region.

Using the minimum mass nebula structure assumed above, 1% of an Earth mass corresponds to 0.2% of the total mass of solids expected to lie between 2.5 and 5 AU of the solar nebula. Thus only a small fraction of material needs to migrate inward to 1 AU to explain Earth's water content. This means that the delivery process need not be very efficient.

A major obstacle for the survival of these bodies as they migrated to the inner nebula would be disruption through collisions with like-sized bodies. As these bodies moved through the nebula, such collisions could occur, breaking the bodies into pieces that would not migrate as rapidly, and therefore inhibit the inward migration of those minerals. The collision time for meter-sized bodies in a swarm with a number density n_p is given by:

$$t_{coll} \sim \frac{1}{n_p \pi r^2 V_{rel}} \quad (3)$$

where r is the radius of the body and V_{rel} is the relative velocity of the particles with respect to one another [32]. It can be shown that meter-sized objects would settle to the midplane to form a layer whose thickness is given by $\sqrt{\frac{\alpha}{2}}H$ where H is the scale height of the nebula and α is the dimensionless turbulence parameter [32]. This would give a particle mass density, ρ_p of $f\sqrt{\frac{2}{\alpha}}\rho_g$ where f is the ratio of the mass of solids to the mass of gas in a canonical nebula (~0.005 inside the snowline) and ρ_g is the local gas mass density. The number density, n_p, would simply be ρ_p/m_p, where m_p is the mass of a meter-sized body. Assuming spherical bodies and that $V_{rel} \sim \sqrt{\alpha}c$ [32] we can re-write the collision time to be

$$t_{coll} \sim \frac{4r\rho_s}{3\sqrt{2}cf\rho_g} \quad (4)$$

where c is the local speed of sound and ρ_s is the material density of the body. Note that this expression is independent of α.

In a minimum mass nebula typical values for the parameters above are gas density of roughly 10^{-9} g/cm^3, $c \sim 10^5$ cm/s, and $\rho_s \sim 3$ g/cm^3, (typical values for about 1 AU in the nebula described above). In looking at the size distribution in coagulation calculations, it has been estimated that meter-sized bodies would make up 10% of the mass of material suspended in the nebula, with the rest of the mass mostly being contained in smaller bodies that would not be able to destroy the larger bodies [3]. Using these values in the expression above, we find that the collisional time for a meter-sized body is ~200 yrs, meaning that a typical phyllosilicate-bearing body originating at 2.5 AU can travel inside the orbit of Venus (moving ~1 AU per 100 yrs as discussed above) before experiencing a collision, though one originating at 5 AU will typically travel to 3 AU before experiencing a collision. Taking the collision timescale to be an e-folding timescale, the fraction of meter-sized bodies that would survive being destroyed by collisions is

$$f_{survive} = e^{-\frac{t}{t_{coll}}} \quad (5)$$

In looking at the most distant travel required, a meter-sized body will drift from 5 AU to 1 AU in approximately 400 yrs giving a survival fraction of 10%. That is, 10% of the meter-sized bodies that would drift in from 5 AU would not be destroyed due to collisions. Those that originated closer in would have a higher survival rate. Thus if only 2% of the mass of the asteroid belt from 2.5 to 5 AU in the nebula model described above was subject to the gas drag-induced migration described, then the necessary mass of water would be delivered to 1 AU. If the 50% retention rate assumed above is too low, then this will require that a higher percentage of the hydrated mass was mobile.

A similar calculation can be done for Mars, assuming that it attained its water in this same way. The recent results of the Martian Exploration Rovers Spirit and Opportunity have demonstrated that Mars once had large amounts of water on or near its surface. Estimates of the total amount of water suggest the water inventory was equivalent to global oceans anywhere from 600 to 2700 m in depth [12]. This corresponds to a total water content of roughly 1–6×10^{-4} Mars masses, requiring 0.1–0.6% of its mass originated in the outer asteroid belt. Because the distance between the Earth and Mars is not large, our model would predict that Mars would have been able to accrete at least the same fraction of hydrous minerals as the Earth, which is consistent with the high ends of the estimated Martian water content. If the Martian water content was somewhat lower, it may have been lost due to accretional and outgassing processes—the fact that Mars' has a lower mass might have made retention of water more difficult. Likewise, bodies which accreted in the inner asteroid belt and appear anhydrous may have not been able to retain their small amount of water content during accretion or subsequent processing, which is why there is no evidence for it. More work is needed to investigate this possibility.

5. Conclusions

Dynamical models have shown that it is possible that water was delivered to Earth by a few large, hydrous planetary embryos and that such a scenario would be consistent with the observed D/H ratios [6,33]. This would generally occur later in the growth phase of the Earth and in random events which could lead to planets with a variety of water contents. While random accretion of gravitationally scattered bodies cannot be ruled out, and in fact likely do occur over the course of planetary accretion, geochemical arguments suggest that hydrous minerals were present early on, in the planetesimals from which the Earth formed. However, current nebular models make such a scenario unlikely, as hydrous minerals would not be able to form locally due to the high temperatures at 1 AU.

Here we have presented a way that hydrous minerals could be carried to where Earth would form without requiring large bodies to have accreted in the asteroid belt first. If hydrous minerals formed prior to the removal of the solar nebula gas, such as in a shock wave [19], they could have been carried into the inner nebula by gas drag processes without losing a significant fraction of their water. There they could be accreted by the growing planetesimals and later incorporated into the proto-Earth, satisfying the need to have water present during the early phases of the formation of the Earth without invoking nebula models that contradict what is observed in meteorites and asteroids. In addition, because it would happen prior to the differentiation of the Earth, the problems of addition as a late veneer [7] are avoided. An important issue that remains to be investigated in any delivery model is whether this is consistent with the delivery of other volatile species to the Earth.

In reality, the delivery of water to the inner nebula likely occurred in a variety of ways. Thus far we have only focused on water being delivered by objects similar to those that are present today. It is also possible that there was a class of water-bearing bodies that played a role in transporting water that no longer exist. However, we are able to explain the delivery of water to Earth in a way that is consistent with the observed D/H ratios in the oceans and the proposed source region. While stochastic events such as the gravitational scattering of large objects may play a role in determining which planets are able to harbor life, the early transport of small, volatile-rich objects cannot be ignored. Such a process would be a natural stage of nebular evolution, particularly in long lived protoplanetary disks, implying that the delivery of hydrous minerals to the habitable zone around a star may be a common occurrence, suggesting that missions such as the Terrestrial Planet Finder and Darwin could possibly find a number of Earth-like planets.

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