RADIAL MIGRATION OF PHYLLOSILICATES IN THE SOLAR NEBULA.

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Introduction: It has long been recognized that the high temperatures of the inner solar nebula (within ∼3 AU) would not have allowed water to be incorporated into solids. However, the presence of water on the surface of Earth, as well as evidence for it on the surface of an early Mars imply that water was incorporated into solid bodies in this region. How this water was delivered to the solid bodies has yet to be identified.

In this abstract we explore the possibility that hydrous minerals, such as phyllosilicates, formed somewhere in the asteroid belt region of the solar nebula or beyond, and then migrated inward where they would be accreted into larger bodies.

Phyllosilicates: A number of carbonaceous chondrites, considered to be among the most primitive objects in the solar system, contain phyllosilicate minerals. These minerals are thought to form either from the interaction of anhydrous rock with water vapor [1] or with liquid water [e.g. 2, among many others].

Up until recently it was thought that the phyllosilicates found in primitive meteorites could not form via gas-solid reactions in the solar nebula because the time needed for the reaction to take place under canonical nebula conditions would be much longer than the lifetime of the solar nebula [2]. Recently, it was argued that the fine-grained phyllosilicates found in chondrule rims could have formed in this manner if large scale shock waves, such as those proposed to form chondrules, operated in icy regions of the solar nebula where ice was enhanced by factors of 100-1000 [1]. Under these conditions, the phyllosilicates could form over a period of days to weeks, which would allow the phyllosilicates to be nebular products.

In the scenario where phyllosilicates formed through reactions with liquid water, the anhydrous rocks would have accreted with water ice, and thus in regions of the nebula where ice had condensed (∼5 AU in the early nebula, ∼3 AU at later stages [3]). The ice would then have melted as the interior temperature of the asteroid rose due accretional energy and the decay of radionuclides. The amount of time needed for the reaction to take place in the presence of liquid water is not known, but is thought to be relatively short [4,5], and thus could have occurred on timescales which are less than the lifetime of the solar nebula.

Migration and Dehydration: Regardless of the mechanism by which they formed, it is possible, if not likely, that phyllosilicates were formed in the solar system before the solar nebula gas was removed. Like all solids, those bodies containing phyllosilicates would have experienced gas drag and migrated inwards while the gas was present. The rate of migration can be calculated using the equations given in [6].

As these bodies migrated inwards, the gas through which they passed would increase in temperature. Eventually they would reach temperatures at which the phyllosilicates were no longer stable. However, if the rate at which the minerals dehydrated was slow enough (compared to migration timescales), the bodies could have migrated very far inwards before releasing water. A similar idea was explored by Cyr [7] by investigating the migration and vaporization of water ice in the nebula.

In our work, we consider chrysotile (taken as a typical phyllosilicate) dehydration to occur when it experiences a collision with the nebular gas which has an energy greater than the activation energy of the dehydration reaction. Experimentally inferred values of the dehydration activation energy range from 300-600 kJ/mole [8] (this experiment specifically looked at the release of water from the phyllosilicate, so we believe that water is a plausible product of the decomposition of the minerals). The gas is assumed to be composed purely of hydrogen, and at each location (temperature) in the nebula, the collision rate of the gas with the surface of the body can be calculated. The fraction of collisions with an energy greater than the activation energy can be calculated as well, following the method used in the Simple Collision Theory of chemical kinetics [2].

In this work we track the evolution of a body composed purely of chrysotile as it migrates inward from a distance of 5 AU. Throughout the time that the body is migrating, the number of collisions with gas molecules of energy greater than the dehydration activation energy is tracked. For each of these collisions we assume that the water in one chrysotile formula unit is released. For large bodies, we assume that diffusion of chrysotile to the surface is not a rate limiting process–that is, each energetic collision causes the dehydration reaction to take place, regardless of where the chrysotile is located in the body.

Nebula Structure Used: As a first case for consideration, we assume a static nebula such that its properties do not change on timescales comparable to the migration times of the bodies of interest. The nebula used here is assumed to be described by the equations given in [3], such that the surface density is a power law function of heliocentric distance, and the temperature of the nebula is determined by the mass accretion rate onto the sun. Specifically, we assume that the surface density of the nebula is proportional to $r^{-1.5}$, with a value of 2000 g/cm^2 at 5 AU. We also assume that the mass accretion rate is 10^{-8} M_{sun}/year and that the nebula has a constant opacity of 5 cm^2/g. This yields a temperature of about 125 K at 5 AU with the ice condensation point (snow line) being at about 4 AU. This structure gives a nebular mass of $\sim$ 0.08 M_{sun} between 4 and 20 AU, which is slightly less massive than those studied by [9]. We are currently investigating other plausible nebula structures.

Migration Results: For comparison purposes, we applied our migration and vaporization model to a case similar to that in [7] by studying water ice particles as they drifted inwards. Our results matched those of that study in that bodies (1cm-10m in radius) of pure water ice could migrate in to about 3 AU before completely vaporizing. This provided verification of our migration model.

In looking at phyllosilicates, we found that they could migrate much further inwards before dehydrating. In fact, for bodies that migrate most rapidly (1cm-10m in radius), these bodies will reach distances of ∼1-1.5 AU before losing significant fractions of their water content. Once reaching these distances, the phyllosilicate bodies are quickly dehydrated. The migration times for these bodies were $<\sim$10,000 years.

Discussion: If phyllosilicates such as those found in primitive meteorites were formed prior to the loss of the nebular gas, the bodies containing these minerals could have been transported large radial distances via gas drag. As these bodies moved inwards and entered warmer regions of the nebula, while the phyllosilicates would not be stable products, they would not begin to significantly dehydrate until they reached temperatures of about ∼500 K or higher. In the nebula model used here, this occurs at heliocentric distances less than ∼1.5 AU.

Those bodies that migrate most rapidly are between 1 cm and 10 m in diameter. It is unknown how common phyllosilicate carrying bodies of this size would be in the solar nebula. If some phyllosilicates formed via gas-solid reactions, bodies of this size would likely form as a step towards accreting larger bodies. If the phyllosilicates formed on larger bodies due to liquid-solid reactions, those bodies may have experienced collisions which ejected bodies of this size [4].

The migration of these particles would allow hydrated minerals to be transported to regions of the nebula where they could not have formed. They could then be incorporated into larger bodies and be shielded from high energy collisions which would cause them to dehydrate. Because large bodies do not migrate significantly, these hydrated minerals could then be accreted by the planets that formed in the inner (hotter) region of the solar system.

It has been argued that the most likely scenario to explain the presence of water on Earth is that Earth accreted from a mixture of hydrous and anhydrous materials rather than having water delivered in a 'late veneer' [10]. If this was the case, then the process outlined above may provide a way that Earth could have accreted hydrous minerals even if the nebula was too hot to allow them to form at ∼1 AU.

The total amount of water in the Earth's hydrosphere is $\sim 1.6 \times 10^{24}$ g [11]. Delivery of this mass of water requires the Earth to have accreted 2.5×10^{25} g of chrysotile, which is ∼0.4% of the total mass of the Earth. Thus, the delivery of hydrated material to the inner solar system need not be very efficient to supply all of the water present on Earth today.

On Mars, the geomorphological features suggest that liquid water was once stable on the surface. Previous estimates suggest that the amount of water on the surface could have been equivalent to a global layer up to 2 km deep [11]. This corresponds to roughly 2.88×10^{23} g of water in the Martian hydrosphere. Thus, Mars may have accreted up to 4.4×10^{24} g (0.7% of its mass) of chrysotile.

These calculations are consistent with our model of rapid phyllosilicate mineral formation in icy regions of the solar nebula followed by radial drift of small bodies containing those minerals. This model predicts that the region of the solar system where Mars accreted would have contained a higher fraction of phyllosilicate material. The Earth would have received less of this material, which would have decomposed as it migrated further inward of 1 AU.

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