THE DISTRIBUTION OF WATER IN A VISCOUS PROTOPLANETARY DISK.

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Introduction: The distribution of water in the solar nebula is important to understand for a number of reasons. Firstly, in the inner regions of the solar nebula, the concentration of water vapor is expected to have played a major role in determining its oxidation state, and therefore would control which minerals would form there [1]. Secondly, in the outer nebula, water would be a major condensable, making up nearly 50% of the mass of the solids and thus possibly playing a role in determing where giant planets formed [2]. Lastly, liquid water is important for forming and sustaining life, and therefore understanding where and how water was transported to the habitable zone of a a star is critical to understanding how common life may be in the galaxy.

Because of its importance, the distribution of water in the solar nebula has been studied by a number of authors [2-5]. The main transport mechanisms which would determine the distribution of water would be diffusion and gas drag migration. Water vapor and small solids would diffuse in the nebula, moving away from areas of high concentrations. Larger bodies, while also subject to diffusion, though to a lesser extent, would experience gas drag migration, causing them to move inwards with time [6]. The bodies most affected by this transport mechanism would be on the order of 1 meter in size. As objects continued to grow larger, their inertia would also grow, making them nearly immobile to gas drag.

While efforts have beeen made to understand how water would be distributed in a protoplanetary disk, none of the published models simultaneously consider the effects of nebular evolution, transport of material throughout the nebula, and the existence of solids of various sizes at a given location of the nebula. We are currently developing a model which allows for these effects and is consistent with models for the accretion of bodies in the solar nebula.

Model for Disk Evolution: For this work, we use the α-viscosity model for disk evolution [7]. In this model, the nebula evolves as a viscous accretion disk, with a local viscosity given by $\alpha c H$, where α is a parameter which measures the strength of the turbulence, c is the local speed of sound, and H is the local scale height. The viscosity of the disk causes some of the mass of the disk to be transported inwards over time, while the rest is transported outwards to conserve angular momentum. As a result of this transport, the disk decreases in mass and grows in radial extent with time. This model has been used to explain the observed structure of disks around T-Tauri stars [8]. The thinning of the disk causes its optical depth to the midplane to decrease, and the nebula cools. This cooling causes the location of condensation fronts, such as the snowline, to migrate inwards with time [9].

Behavior of Solids in a Viscous Disk: In our model, we consider the transport, growth and destruction of solids. The dynamic behavior of the solids depends on their sizes, and we consider three size ranges: *dust* ($St << 1$, where St is the Stokes number and is equal to the stopping time of the particle times the local Keplerian rotation rate), *migrators* ($St \sim 1$), and *planetesimals* ($St >> 1$). We also track the distribution of water vapor.

Along with the evolution of the nebula, the viscosity of the disk creates a diffusivity which causes material to be transported within it. The diffusivity of a given species is given by $\alpha c H/(1+St)$. This means that vapor and small solids (*dust*) will be transported most easily by diffusion, while larger bodies, such as *planetesimals*, will hardly be affected.

The population of *migrators* represents the inetermediate-sized bodies that are typically ~1 meter in diameter. These bodies are those that are most strongly affected by gas drag effects [6], and as a result, migrate inwards at rates of ~1AU/100 years. This transport velocity is much greater than those due to diffusion or advection, and thus this process tends to dominate the transport of solid material in the protoplanetary disk.

As particles move within the nebula, they will experience collisions which will lead to both growth and destruction. We characterize the growth of migrators and planetesimals by the timescales t_{coag} and t_{acc}, which are constrained by accretion models. These timescales generally scale with orbital period [10], and t_{coag}=10^3-10^4 yrs is roughly appropriate for 1 AU [11]. The timescale for planetesimal formation is less defined, as we have yet to identify how planetesimals form. Thus we consider a range of values for t_{acc}. Migrators and planetesimals are also allowed to grow by sweeping up smaller particles, and migrators can be destroyed by turbulence induced collisions.

As species move within the nebula, they experience different thermal conditions. As solids are transported into warm regions, they vaporize at a rate given by [12]. Similarly, as water vapor is transported into cooler regions of the nebula, dust will condense in order to ensure that the actual water vapor pressure does not exceed the equilibrium value.

Preliminary Results of Model Runs: Below we describe the insight gained by one of our simple model runs, where we study the evolution of a disk with α=10^{-4} and an initial surface density distribution of Σ=2000(1AU/r) g/cm^2 out to 50 AU (giving a total mass of 0.07$M_\odot$). We set the values of t_{coag} and t_{acc} to each equal 10^4 years. Some of the results of our model run are shown in the figure below. Here we briefly discuss some of the implications these results have for various aspects of the formation of the solar system.

Primitive Meteorites: The inward mass flux of the *migrators* is initially greater than the outward diffusion of the water vapor, resulting in a vapor pile-up inside the snowline and an oxidizing chemical environment. As the nebula evolves, the pile-up will grow initially and spread throughout the inner nebula, resulting in enhancements of the water vapor by more than an order of magnitude, as predicted by [5], and is illustrated below. As planetesimals grow in the outer nebula, the inward mass flux of migrators slows, and the water vapor is advected towards the sun or diffused outward faster than it is replenished. This results in the water vapor concentration decreasing with time, and it eventually decreases below the canonical solar value, producing a more reducing chemical environment. Similar fluctuations in the oxygen fugacity of the inner nebula are seen in the chondritic record, as the FeO content of some meteorites requires highly oxidizing conditions whereas the mineralogy of the enstatite chondrites can best be explained under reducing conditions [1,13,14].

Giant Planet Formation: In order to form Jupiter via the core accretion mechanism, the core must grow rapidly in order to accrete enough neubular material before it is removed. In order to do so, it was suggested that the cores of giant planets could form in a region of the nebula where solids were sufficiently concentrated. The largest pile-up of solids occurs immediately outside the snowline at 2 AU in these simulations, where the surface density of solids is quickly enhanced by factors of ∼40, consistent with the results of [2].

Nebular Structure: The structure of the solar nebula and of other protoplanetary disks is often inferred by measuring the mass of planets (or solids) in the disk and then inferring how much gas must have been there (or is currently there) to reproduce a solar composition. However, the transport of solids throughout the disk can lead to solids-to-gas ratios that vary both with time and location in the disk. Thus, inferring the surface density of the gas from the amount of solids in the disk may lead to significant errors.

In addition, because migrators cause the preferred direction of solid transport to be inward, the amount of solid building material that would be lost to the sun is large. This causes the average solids-to-gas ratio for the entire solar nebula to decrease with time. In the case studied here, the initial solids-to-gas ratio had the canonical value of 4.5x10^{-3}, but after 3 million years decreased to less than 10^{-3}.

Summary: We have developed a new model to track the evolution of water in viscous protoplanetary disks. Our model qualitatively predicts similar evolutionary stages as those that have been discussed in previous studies, but differs quantitatively due to the detailed treatment of the finite disk mass and allowing solids of different sizes to coexist at a given location of the nebula. The evolution described here is also applicable to a number of volatiles in the solar nebula which may exhibit similar behavior.

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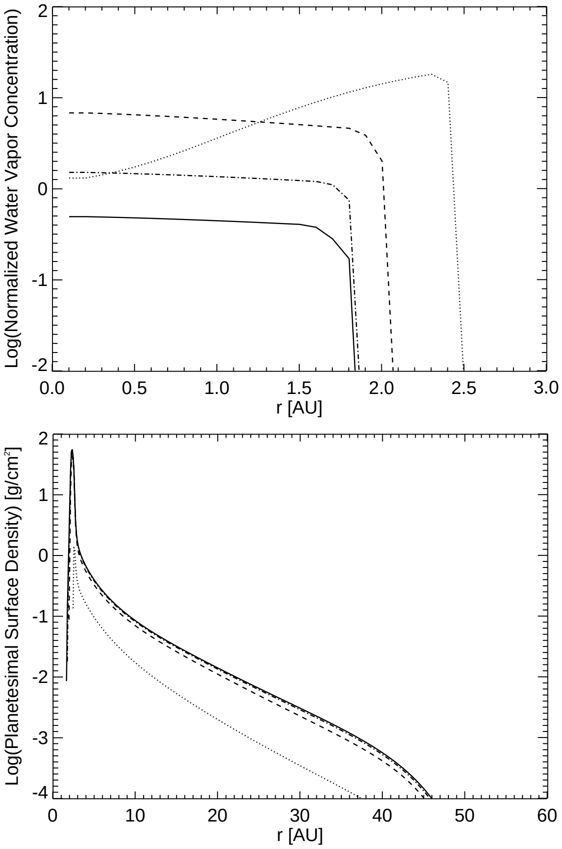

Figure1: The evoulution of the water vapor (top) and planetesimal (bottom) distributions in the protoplanetary disks. Plotted are snapshots of the distribution at 10^5 (dots), 10^6 (dashes), 2x10^6 (dash-dots), and 3x10^6 (solid) years.