ENHANCEMENTS OF WATER NEAR THE SNOWLINE: TWO-DIMENSIONAL CONSIDERATIONS.
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Introduction: The dynamical evolution of water in the solar nebula is of interest for a number of reasons. In the gas phase, the abundance of water would have played a key role in setting the oxidation state of the nebula, and thus was one of the determining factors in what minerals would form [e.g. 1]. Recently it has been argued that this water may have also been preferentially enriched in heavy oxygen, perhaps through photochemical effects [2-4], and the variations in its abundance therefore is what is responsible for the ranges in oxygen isotope ratios seen in primitive materials [5]. In the cooler, outer solar nebula, water ice would have made up a significant fraction of the mass of solids and planet-forming materials [6] and therefore its distribution may have been responsible for determining the timing and location of giant planet formation [7,8]. Here I examine the dynamical effects that would have affected the distribution of water in the solar nebula and evaluate what role these effects may have had in impacting the early stages of solar system formation.

Previous Work: Water in the solar nebula would have been affected by such dynamical processes as diffusion, gas drag migration, large-scale advective flows, and vertical settling. In [7], the outward diffusion of water vapor from the inner solar nebula was shown to lead to the enhancement of solid material just beyond the snow line, allowing for more rapid formation of a proto-Jupiter core. In [8] it was shown that the inward drift of water ice from the outer solar nebula due to gas drag [e.g. 9] would also lead to the pile-up of solids near the snow line, which would also increase the rate at which a giant planet core would form.

As drifting boulders of water ice crossed the snow line, they would vaporize, losing their water to the gas. As the inward (advective) movement of water vapor would be much slower than the inward drift of solids, this evolution would lead to a localized enhancement in water vapor [10]. The level of enhancement depended on many factors, but initially, increases in the water vapor abundance by factors of 100-1000 were thought to be possible, consistent with the levels needed to produce the oxidized minerals observed in chondritic meteorites [1]. Subsequent detailed numerical investigations [11] showed that the enhancements were actually limited by the finite amount of water that was present in the outer disk to drift inwards, and that enhancements greater than 10x were difficult to achieve within the solar nebula.

Two-dimensional Considerations: All previous modeling efforts have been done in one-dimension. These models have the potential of overlooking two important effects that would impact the particular dynamical evolution of water in the solar nebula. The first is the fact that when the most rapidly inward migrating icy bodies (~1 meter-sized) cross the snow line, they will have settled into a thin layer around the midplane. In one-dimensional models it is assumed that the vapor released from such bodies was *instantaneously* redistributed such that it had a uniform concentration with height above the midplane. However, because this redistribution will take a finite period of time, the water vapor concentration is expected vary with height, with highest concentrations being reached around the midplane. For example, if water ice was carried across the snow line predominantly by meter-sized bodies, these objects will have settled into a thickness of $H_{ice}=(\alpha/2)^{1/2}H$, where H is the scale-height of the gas and α is the turbulence parameter which characterizes the diffusivity and mass transport rate of the solar nebula [e.g. 12]. For $\alpha=10^{-4}$, the ice would be concentrated within a height of $0.007H$. If meter-sized bodies drifted inward rapidly enough to double the concentration of water just inside the snow line in the 1D models, this would result in an increase in the water concentration by ~140x in the volume in which the water ice vaporized, provided that the vertical diffusion time was small compared to the inward drift rate of the ice. Thus the 1D model would grossly underestimate the maximum water enhancement that would actually develop around the midplane.

The second effect that would be overlooked in the 1D models is that there are variations in the radial transport rate of materials with height above the disk midplane. In 1D models, the vapor that was released by the inward drifting icy boulders was redistributed by diffusion and the net inward flow associated with the evolution of the solar nebula [10,11]. Two-dimensional models, however, indicate that the viscous evolution of a protoplanetary disk results in outward flows around the disk midplane. These flows, when combined with the diffusion within the disk, would serve to efficiently transport material outwards in this region, explaining the presence of high temperature materials collected by the Stardust mission [13]. In the case considered here, as the vapor from inward drifting ice would be released within these outward flows, it would likely be preserved to a higher degree in the disk as it would move outwards across the snow line and recondense as water ice, rather than move inward and be lost to the sun as rapidly as the 1D models would predict. This would allow for more efficient recycling of the water, and perhaps, longer-lived enhancements of the water vapor concentrations as the outer disk would not become depleted in water ice as rapidly. This would also allow for greater retention of solid-forming materials, which would increase the efficiency of planet formation.

New Model: I have modified the two-dimensional model used in [13] to track the dynamical evolution of water vapor, icy dust, icy migrators, and icy planetesimals within an evolving solar nebula. The rate of mass exchange between each species is determined as in [11]--through the definition of coagulation and accretional timescales as well as by vaporization and condensation when conditions call for it. A range of growth timescales and disk structures are currently being investigated in order to evaluate the level to which water vapor is enhanced within the solar nebula, the volume of the nebula which is significantly enhanced in water vapor, and the period of time over which such enhancements would persist.

Preliminary Results: The initial runs of the new model indicate that larger water vapor enhancements do develop within the solar nebula than were found by the 1D modles of [11] as predicted. Maximum enhancements of 100x solar are relatively easy to achieve, with 200-500 also being possible depending on the choice of disk structure and transport parameters. These larger enhancements are limited to within ~0.5 AU of the snow line and ~0.1-0.15 AU of the midplane, however, as opposed to being uniform throughout the inner nebula. This suggests that, counter to general expectations, the mixing and transport processes within the solar nebula could have led to strong spatial gradients in the oxidation state and oxygen isotopic ratios.

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