SNOW LINES IN EXTERNALLY PHOTOEVAPORATED PROTOPLANETARY DISKS.

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Background: The inner solar system is marked by a lack of water. The mass fraction of water on Earth is < 0.1wt% [1], yet the mass fraction of water in the outer solar system is > 40 wt%. During accretion in the solar nebula, a "snow line" existed outside which planetary bodies accreted ice, inside of which ice was depleted by factors > 400. If the disk temperature falls below the condensation temperature of ice ($\approx 170\,\mathrm{K}$, [2]) at heliocentric distance $R_{\rm ice}$, Water vapor from inside $R_{\rm ice}$ can diffuse beyond $R_{\rm ice}$, condense into large bodies there, and be "'cold trapped" [3]. While the present day blackbody temperature is 170 K at 2.7 AU, temperatures in the disk, when ice condensed, were much colder. Models predict $R_{\rm ice} \approx 0.8 - 2.2\,\mathrm{AU}$, depending on the rate of mass accretion and heating [4-9]. Recently [10] have shown that accretional heating is less effective than previously thought: the most probable cause of accretion is the magnetorotational instability, which acts only in the surface layers [11]. Heat generated in surface layers more easily escapes the disk, minimizing the effects of accretion on midplane temperatures, and keeing $R_{\rm ice}$ close to 0.8 AU even for $\sim 10^{-8}\,M_{\odot}\,\mathrm{yr}^{-1}$ [10]. Generally $R_{\rm ice}$ varies in time, being far out when accretion heating is stronger, and moving inward as the disk cools. Cold-trapping of water during an early stage potentially could explain the depletion in the inner solar system. The main difficulty with this explanation is that ice should return to $r < R_{\rm ice}$ by diffusion, inward advection of the disk, or, especially, drift of meter-sized ice bodies relative to the gas [12-13]. It is difficult to explain why the inner solar nebula was both so dry and so cold.

The Inner Solar Nebula as Antarctica: I propose that the inner solar nebula was indeed cold enough for ice to condense, but was simply devoid of water vapor. I propose as others do that water was cold-trapped beyond 4 AU during an early stage of disk evolution when temperatures were high. In contrast to other models, I propose that this ice beyond 4 AU was prevented from returning to the inner disk because the solar nebula transitioned early on to a *decretion* disk as mass was removed from its outer edge by external photoevaporation, as proposed by [14]. The outward flow of gas, combined with the inward drift of ice with respect to the gas, prevented the inward flow of cold-trapped ice.

I have constructed a very simplified model that captures the essential physics and demonstrates the effect of external photoevaporation on the snow line. This model solves the standard equations for the flow of material and the evolution of the surface density Σ assuming an α viscosity $\nu = \alpha C H$, where C is the sound speed, $H = C/\Omega$ the disk scale height, Ω the Keplerian frequency, and assuming a vertically averaged $\alpha = 10^{-2}$. The disk midplane temperature is set to the effective temperature, where $T_{\rm eff}^4 = T_{\rm psv}^4 + \tau (9/8) \Sigma \nu \Omega^2$, with the optical depth τ fixed to 100 to mimic the finding of [15] that the surface densities of actively accreting layers are $\sim 3\,\mathrm{g\,cm^{-2}}$ and opacities are $\sim 30\,\mathrm{cm^2\,g^{-1}}$. Here $T_{\rm psv} = 100\,(r/1\,\mathrm{AU})^{-1/2}\,\mathrm{K}$ is the temperature of a passively heated disk [10]. Diffusion of water vapor is included assuming a diffusivity equal to the viscosity. I allow for water to transition between ice and vapor on a timescale $t_{\rm frz} \sim 10^4\,\mathrm{yr}$. I also consider the inward drift of solid ice with respect to the gas at a speed $1\,\mathrm{m\,s^{-1}}$. I then consider two scenarios for disk evolution: a "non-photoevaporated" disk, and a "photoevaporated" disk in which gas is removed from the outer edge on a local timescale $t_{\rm evap}(r)$. I crudely set $t_{\rm evap}(r) = 10^7\,(r/60\,\mathrm{AU})^{-15}\,\mathrm{yr}$ to that mass accretion is very rapid at large r and slow at small r, mimicking a disk edge at 60 AU like that inferred by [14].

In the non-photoevaporated case, the surface density, initialized to $1700 (r/1\,\mathrm{AU})^{-1}\,\mathrm{g\,cm^{-2}}$, evolves to a near steady-state $r^{-1.15}$ profile. The temperatures quickly converge on $R_{\rm ice} = 4\,\mathrm{AU}$ and evolve little. Mass flow is inward ($\dot{M} > 0$) at all radii at all times, is nearly uniform, but decreases from $\sim 10^{-8}\,M_{\odot}\,\mathrm{yr}^{-1}$ to $\sim 10^{-9}\,M_{\odot}\,\mathrm{yr}^{-1}$ over 5 Myr. The surface density of ice shows a clear snow line at 4 AU, but with substantial condensation of ice from 3 to 4 AU. As the disk evolves and cools, water vapor tends to condense inside $R_{\rm ice}$ before it can diffuse past $R_{\rm ice}$.

In the photoevaporated case, the disk mass drops considerably over time as mass is removed at the outer boundary, and $\Sigma(r)$ decreases as it also becomes steeper ($r^{-1.7}$ in this case). Temperatures drop as $\Sigma(r)$ decreases, becoming even colder than the non-photoevaporated disk as a result. Mass flow is outward ($\dot{M} < 0$) at all radii at all times, comparable to $10^{-8}\,M_\odot\,\mathrm{yr}^{-1}$ but decreasing.

Removal of water from the inner solar nebula may require both cold-trapping beyond an early snow line R_{ice} that is $\gg 1$ AU because of accretional heating, PLUS outward advection of this ice due to decretion, probably driven by external photoevaporation. This suggests that in solar systems that did not form near massive stars, more water could have diffused into the inner disk and produced ice-rich planets.

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