DEPLETION OF MODERATELY VOLATILE ELEMENTS BY OPEN-SYSTEM LOSS IN THE EARLY SOLAR NEBULA.
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Introduction: Rocky bodies of the inner solar system display a systematic depletion of the "Moderately Volatile Elements" (MVEs) that correlates with the expected condensation temperature T_C of their likely host materials under typical protoplanetary nebula conditions $[1, 2]$. The elements in question have T_C ranging from roughly 600K (Zn, S) to 1400K (Ni, Fe, Mg, Si). The exact depletion signature and other details of the T_C dependence vary from object to object but the overall trend itself is ubiquitous. The depletion affects both carbonaceous and non-carbonaceous meteorites, which are believed to have formed in regions that were prevented from mixing from less than 1Myr after CAI, suggesting that the depletion is a very early process. Several avenues addresing this long-standing problem includes the incomplete condensation of the nebular gas $[3, 4]$, mixing of volatile-rich and volatile-poor meteoritic components $[5]$, an MVE-depleted molecular cloud during the formation of the Sun $[6]$, or a natural outcome of the mixing of solids and planetesimal formation during the very early cooling of the solar nebula $[7, 8, 9]$. However, these efforts are yet to reproduce the depletion trend with a physically consistent range of parameters. However, it is important to note that $[9]$ points out several important problems with the concept of such early planetesimal formation during the time when the nebula was still cooling.

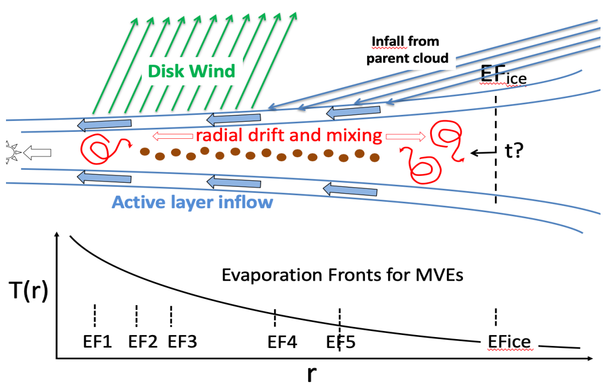

Figure 1: *Diagram showing the concept of our hypothesis of disk wind and MVE depletion. MVEs in vapor form escape the disk through disk winds. The solids are mixed radially due to advection and diffusion. The radial temperature profile sets the evaporation fronts for different species at different radial distances from the star. Due to the weak radial variation of the wind mass loss rate, but the increasing surface area covered by cooler temperatures, a systematic depletion of the MVE species according to their evaporation temperatures is expected.*

Yound disks are not closed system. The early nebulae are highly active, with gravitational instabilities, turbulent viscosity and/or magnetic stresses driving accretion onto the star, all with associated heating and evaporation of different materials, and a highly luminous central star. Here, we present and test a new hypothesis that Disk Winds, as an "open-system" process

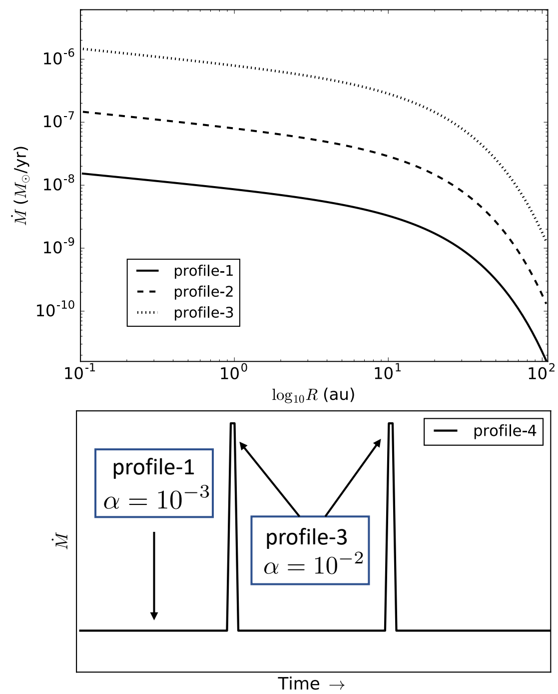

Figure 2: *The wind profile we have used in our model. The bottom panel shows the wind profile that mimics the intense short outburst events in the early nebula*

and which can extend across most of the solar nebula, remove the vapor phase materials including the MVEs, leaving nearly all forms of more refractory solids behind. As temperature decreases, the MVEs, having escaped irreversibly, are no longer available to recondense, so planetesimals can keep accreting the remaining refractory material for several million years, with slightly different classes of chondrites resulting due to the lack of the full spectrum of the more volatile MVEs.

In order to test our hypothesis, we have implemented disk winds in a global 1+1D nebula evolution model for solid and gas $[10]$ and added 11 MVE species to the numerical model which tracks each individual species through advection and diffusion in both solid and vapor form.

Disk Model For Global Evolution of Dust and Gas: Our global nebula evolution model calculates the 1D evolution of the disk surface density $\Sigma(r, t)$ and radial drift velocity $v_{gas}(r, t)$ with a turbulent viscosity prescription $\nu_T = \alpha c_s H$, where c_s is the local sound speed and $H = c_s/\Omega$ is the gas scale-height, with Ω being the local orbital frequency. The equations for the gas component can be written as,

$$\frac{\partial \Sigma}{\partial t} = \frac{3}{r}\frac{\partial}{\partial r}\left[r^{1/2}\frac{\partial}{\partial r}\left(r^{1/2}\nu_T\Sigma\right)\right] \quad (1)$$

and

$$v_{gas} = -\frac{3}{r^{1/2}\Sigma}\frac{\partial}{\partial r}(r^{1/2}\nu_T\Sigma), \quad (2)$$

The model also tracks the *advection-diffusion of particles and trace-vapors* by determining the radial motion of vapor and solid-fractions $f_{v,p}$ of all condensible species using the advection-diffusion equation

$$\frac{\partial \Sigma^i_{v,p}}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left[r\Sigma D^i_{v,p}\frac{\partial f^i_{v,p}}{\partial r} - r v_{v,p}\Sigma^i_{v,p}\right] + S^i \quad (3)$$

where $\Sigma^i_{v,p}$ is the surface density and $f^i_{v,p}$ is the vertically integrated mass fraction of particles (p) and vapor (v) of the i^{th} species. The term S^i represents sources and sinks for particles and vapor of species i. Each species i has an "Evaporation Front" or EF location of which is determined by its 50% condensation temperature, outwards of which it is solid and inwards of which it is vapor [10].

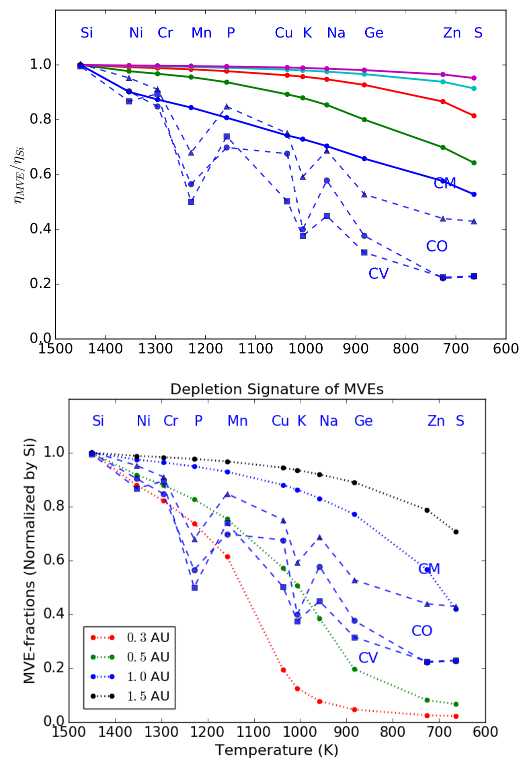

Figure 3: *The results from our simulations: the top panel is the depletion signature for* $\alpha = 10^{-3}$ *with wind profile 1. The signature shown here is obtained at* 50, 000 *years after which disk cooling and inward drift of solids starts to nullify the signature. The figure at the bottom is the depletion signature after only* 10, 000 *years with the same value of* α *but with a higher wind mass loss with profile 3 of figure 2.*

Wind Model: We use the weak disk-wind model by [11] and implement it in the global evolution code by adding a term $\dot{\Sigma}_{wind}$ to equation 1 (and 3). Here $\dot{\Sigma}_{wind}$ is the mass loss rate due to the disk wind. Following [11],

$$\dot{\Sigma}_{wind} = (\rho v_z)_{wind} = C_W(\rho c_s)_{midplane}, \quad (4)$$

where C_W is a parameter regulating the wind mass flux.

The said wind model is parametrized using three free parameters, representing three distinct physical processes: viscous accretion ($\alpha_{r\phi}$), wind mass-loss (C_W), and accretion due to wind driven torque ($\alpha_{\phi z}$). The model considers disk turbulence, irrespective of its nature and origin. In our global simulations, the value of C_W is varied to control the flux of the wind and the radial extent through which gas and vapor escape the disk. Several combinations of C_W and $\alpha_{r\phi}$ are used to perform a systematic study on the interplay of mass loss from disk winds and viscous accretion. In figure 2, we present the wind profiles used in our work.

Updated Gas Opacities: In order to compute the temperature consistently, we calculate the Rosseland and Planck mean opacities for the solids component using effective medium theory with realistic material refractive indices for our suite of cosmic abundance species [12]. We also include the corresponding mean gas opacities computed using the prescription from [13] which covers the range of temperature, pressure and metallicities, particularly relevant for hot inner regions of the nebula.

Initial Results: The top panel of figure 3 shows the results from our simulations with $\alpha_{r\phi} = 10^{-3}$ and a wind mass loss with profile 1 (See figure 2). The results shown is the depletion signature obtained at 50, 000 years. After this point, the nebula cools down and inward drift of the solids become significant, slowly starting to nullify the signature. The bottom panel of figure 3 is the same simulation with a higher mass loss rate (profile 3 of figure 2) where a desired depletion signature is obtained in only 10, 000 years.In all our simulations, we observe diffusive mixing to and from different radii act against the depletion trend in the later part of the evolution.

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