DEPLETION OF MODERATELY VOLATILE ELEMENTS IN CHONDRITES BY OPEN-SYSTEM LOSS IN THE EARLY SOLAR NEBULA.

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Introduction: Rocky bodies of the inner solar system - from 100km diameter, never-melted parent planetesimals of chondritic meteorites, to Mars and the Earth - 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 protoplanetary nebula conditions $[1, 2]$. The elements in question have T_C ranging from roughly 650K (Zn, S) to 1350K (Ni, Fe, Mg, Si) and are found depleted in both carbonaceous chondrites (CCs) and non-carbonaceous chondrites (NCs). The details of the depletion signature vary from object to object but the signature itself is ubiquitous. The CCs and NCs are believed to have formed in regions that were prevented from mixing from less than 1Myr until more than 2Myr after CAIs formed, suggesting that the depletion is a very early process [3]. Attempts to address this long-standing problem go back decades [4-7]. The most popular hypothesis for a while relied on planetesimal accumulation during the very early, hot solar nebula [8-10]. However, significant problems were pointed out with this general concept due to the requirement for planetesimal formation during the short time when the nebula was still cooling [11], in conflict with chondule and chondrite formation ages.

Previous models of hot early nebula MVE depletion [8-10] treated the early nebula as dynamically and chemically "closed"; that is, material only transforms from solid to vapor and back again as temperature changes, but is not gained or lost except to planetesimals. However, early disks are highly active in the epoch of the first planetesimal formation [3], with strong ongoing mass loss (by disk winds and/or layered accretion), ongoing infall from the parent cloud, and rapid expansion and/or mixing driven by gravitational instabilities [12,13], meaning the system is not closed.

Here, we present a new "open" system model in which disk winds or layered accretion, which can extend across most of the inner solar nebula, irreversibly remove the MVEs in their vapor phase at high altitudes, leaving more refractory solids behind in large particles near the midplane (see figure 1, top 2 panels). When the nebula cools, some of the MVEs, having escaped irreversibly, are no longer available to recondense, so planetesimals can accrete even after several million years as observed, with different classes of chondrites resulting from their accretion of material with different MVE depletions. Our model can be thought of as the first stage in the scenario of [14], producing MVE-depleted, hot inner disk material which rapidly expands outwards (perhaps by gravitational instabilities) and becomes truncated at the snowline by a growing Jupiter core, with the ultimately CC material continuing to mix with unprocessed material outside the boundary and the ultimately NC material continuing to feel the effects of ongoing infall inside it.

Code updates: In order to test our hypothesis, we have incorporated a generic mass loss process to represent the effects of either disk winds $[15]$ or layered accretion $[13]$, into an existing global 1+1D viscous nebula evolution model for solids and gas $[16]$. Three radial mass loss profiles $\dot{\Sigma}$ were studied based on the disk wind physics of [15], with different rates adopted to model the depletion signature. We denote profile-1, profile-2, and profile-3 respectively as having disk-integrated rates of $\dot{\Sigma} = 2 \times 10^{-7}, 10^{-6}$, and $10^{-5} M_{\odot}$/year (not unreasonable for young disks). A time-variable mass loss profile is also implemented to mimic the multiple outburst events seen in early disk stages when material may be repeatedly driven outward and mixed [12,13] (see figure 1, bottom).

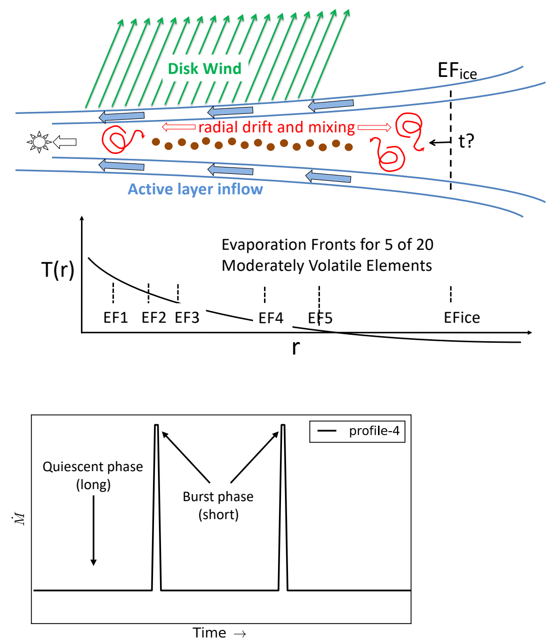

Figure 1: *The top panel sketches the open system mass losses from high altitudes either away from the system (winds) or into the star (layered accretion or active layer inflow). The middle panel shows a schematic radial midplane temperature profile with locations of Evaporation Fronts (EF1..EF5) where different MVEs evaporate, as well as the water ice EF). The bottom panel shows a time sequence we call profile-4, with brief episodes of high mass loss and radial mixing (perhaps due to gravitational instabilities) separated by longer periods at lower disk wind/layered accretion mass loss rates corresponding to profiles 1-3.*

To the realistic radiative transfer modeling of the opacity of nebula solids already implemented by [16], we have added the gas opacities from $[17]$, covering the range of temperature, pressure and metallicities relevant for hot inner regions of the nebula. We do not yet model infall, and have restricted ourselves to modeling the CCs, as the MVE signature of the NCs is more complex and may represent subsequent processing.

Results: In figure 2 we show some typical results. In the first four sub-figures (panel a-d) the MVE depletion signatures are shown at four different radii: 0.3, 0.5, 0.75 and 1 AU. We tested different values of the disk turbulent viscosity parameter α. Panel (a) shows the depletion signature of MVEs from simulation wth $\alpha = 10^{-3}$ and profile-1 mass loss at 50k yrs. After an initial depletion the signature becomes stagnant due to the nullifying effects of (a) disc cooling and (b) inward drift of solid materials (replenishing the MVE inventory in the inner nebula). However, the desired depletion level is achieved with the slightly higher mass loss rate of profile-2 (panel b) where the signature is obtained in 15k years. In panel (c), the profile-3 mass loss reaches the desired depletion level within 2.5k yrs. In both (b) and (c), the MVEs are depleted in a timescale short enough for the disk cooling and inward drift to have only a limited effect on the signature. In panel (d), similar depletion is achieved with $\alpha = 10^{-4}$ and profile-2 mass loss rate. The scenario we currently think most likely to satisfy

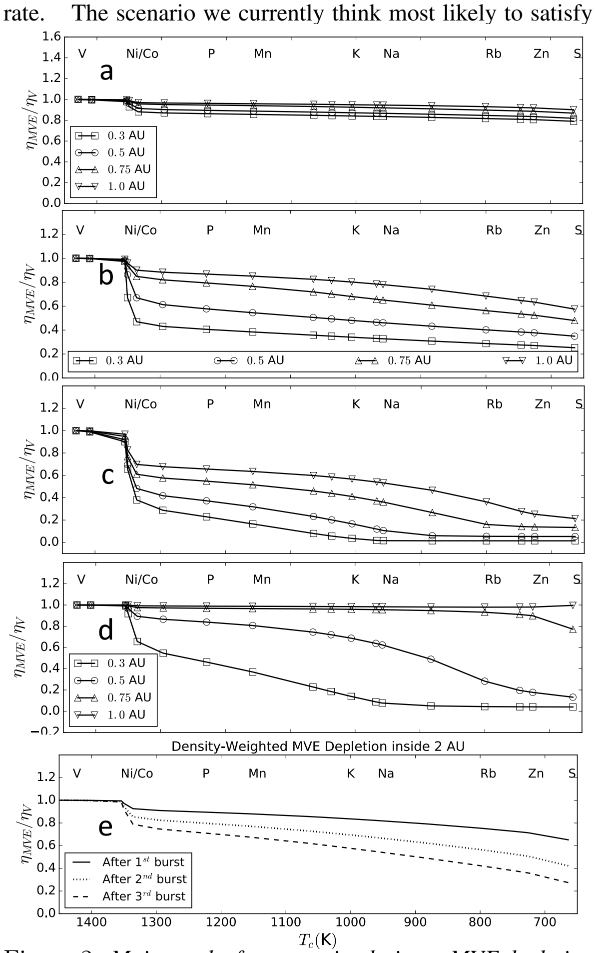

Figure 2: *Main results from our simulations: MVE depletion signature for* **(a)** $\alpha = 10^{-3}$ *with profile-1 mass loss at* 50*k yrs;* **(b)** $\alpha = 10^{-3}$ *with profile-2 mass loss at* 15*k yrs;* **(c)** $\alpha = 10^{-3}$ *with profile-3 mass loss at* 2.5*k yrs;* **(d)** $\alpha = 10^{-4}$ *with profile-2 mass loss at* 15*k yrs.* **(e)** *Signatures for MVEs after the MVE-depleted material is mixed with unprocessed outer nebula material out to 2AU during three consecutive bursts with profile-4 mass loss.*

the observations is *a series of repeated depletions* by moderate strength (profile-2) disk winds acting during quiescent viscous evolution, each lasting for a period $10 - 15$k years, and each terminated by a short burst of high mass loss and dramatic radial mixing outwards. Finally, in panel (e), we show a simple proof of concept where the inner nebula material, depleted in MVEs, is mixed with undepleted disk material of CI abundances after each outburst event as depicted in the bottom panel of figure 1. After each burst and mixing event, the overall abundances of the MVEs go down systematically through the entire mixing region. Based on these initial results, we anticipate that a few more depletion-and-mixing cycles will continue to drive the depletion signature lower and produce the flat baselines as seen in figures 2(a-d), now across the entire mixing region. Moreover, figure 2(e) is a conservative estimate of the overall depletion, as the actual mixing is not modeled and the inward drifting solids in this simple model always have CI-composition instead of becoming successively more depleted in MVEs each cycle.

Figure 3 shows the abundances of an expanded set of elements all the way to the highly refractory Zr and Hf, normalized to Mg (top) and to Zr (bottom). The top plot is the usual presentation and shows the traditional "enrichment" of refractory elements, often ascribed to an overabundance of CAIs that requires an explanation (eg, [18]). However, the bottom plot shows that the same relative abundances can be thought of as a depletion of everything *except* the most refractory elements due to open system losses in a hot, early, inner nebula. If the common rock-forming elements (Fe, Mg, Si) are themselves depleted - a natural outcome of the process we describe - normalization to one of them makes the undepleted refractories appear to be enriched (see also [19-22]). Of course, the details of these profiles are model-dependent.

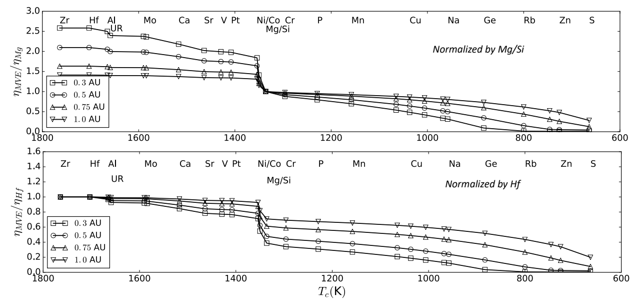

Figure 3: *MVE depletion shown with two different normalizations. In the top panel, the abundances are normalized by Mg-Si. In the bottom panel the same are plotted normalized by Zr-Hf.*

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