COOLING OFF THE SOLAR NEBULA: THE ORIGIN OF MODERATELY VOLATILE ELEMENT DEPLETIONS IN CHONDRITIC METEORITES.

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Introduction: The origin of the MOderately Volatile Element (MOVE) depletions in non-CI chondritic meteorites has been the subject of study and debate for over four decades [1-6]. The MOVEs are defined as those elements which condense at temperatures between ~650 and 1350 K under solar nebula conditions, and the depletions are observed as a trend in which the CI-normalized abundances of these MOVEs decrease with decreasing condensation temperature. Two main varieties of models have been proposed to explain these trends: 1) two component mixing models which suggest that chondrites are the mixture of volatile-depleted and volatile-rich materials at various proportions, and 2) incomplete condensation models that argue that the depletion trends are the result of condensation taking place in a system in which gas is constantly being removed as the temperatures decrease.

Cassen [3] showed that the depletion trends could be reproduced via incomplete condensation if condensation occurred in a solar nebula that was evolving due to mass and angular momentum transport. The disk would cool as it thinned, its mass transport rate diminished, and as dust coagulated allowing radiation to escape more easily. Planetesimals grew from the solids that were present at a given location, and therefore accreted more volatile-rich materials with time. However, because the cooling was associated with mass loss from the disk, the available volatile inventory was diminished compared to the less-volatile materials that condensed during an earlier (hotter) phase. In this manner, Cassen [3] attributed the MOVE depletion trend to be due to the natural evolution of the solar nebula from an initially hot state (T>1350 K in the chondrite formation region).

Here this evolution is reinvestigaged using a new model for protoplanetary disk chemical and physical evolution. This new model is similar to those used to describe the structure and evolution of protoplanetary disks observed around young stars, and tracks the radial migration of solids and vapor due to advection, diffusion, and gas drag. The major change from the model of Cassen [3] is in the treatment of migration of materials via gas drag and the allowance for vapor redistribution via diffusion.

The Model: The model used here is based on that developed by Ciesla and Cuzzi [7]. The evolution of the solar nebula is calculated by assuming a viscosity of $\alpha c H$, with α being a free parameter with a value <1. The solar nebula is assumed to have some initial structure with dust uniformly suspended within in it. The evolution of the solar nebula is then calculated, with the temperature being determined by the balance between internal heat generated by viscous dissipation and that which could be radiated from the surface.

Because the MOVEs are expected to mainly be trace elements and not add significant mass to the condensed materials in the solar nebula, solids are considered to be made of Mg-silicates and Fe-metal. Solids are considered to exist in three dynamical categories: *dust* (small particles with Stokes numbers, *St*, << 1), *migrators* (*St*~1) and *planetesimals* (*St*>>1). The formation of migrators from dust is determined by a parameter, t_{coag}, and the formation of planetesimals from migrators is determined by a parameter, t_{acc}. The dust particles are strongly coupled to the nebula gas, and follow the gas in terms of their dynamical evolution. Migrators begin to decouple from the gas, and while they diffuse to a lesser extent than the dust, they drift inwards due to gas drag at rates that are determined by the local pressure gradient. Planetesimals are expected to only be weakly affected by the presence of any gas in the nebula, and therefore are assumed to follow Keplerian orbits at the location that they form. At high temperatures (T>1350 K) the solids are assumed to vaporize, and the dynamic evolution of their vapor is also tracked.

The model is used to track the distribution of an element, *E*, with a condensation temperature of T_c. Thus two types of solids are tracked: those in which *E* has condensed, and those in which *E* has not. Initially the solids are distributed such that at T>1350 K, all materials exist as vapor, at 1350 K < T < T_c the solids have condensed with *E* remaining in the vapor, and at T < T_c, the solids have incorporated *E*. We track the evolution of the solids and determine the relative abundance of *E* in the planetesimals that form as a function of time and location. This calculation is done for different assumed condensation temperatures, and from these results we determine the elemental depletion trend. An example of one of the model runs is shown in Figure 1.

Model Results: The model has been applied to look at a variety of disk structures and evolutionary parameters. It is found that, in agreement with Cassen [3], the MOVE depletion trend can be reproduced by the formation of planetesimals in a solar nebula that cools from an initially hot state, ***provided*** certain conditions are met.

Firstly, the solar nebula must initially be hot enough to achieve temperatures above 1350 K in the chondrite formation region (assumed to be >2.5 AU). This generally requires mass accretion rates through the solar nebula in excess of 10^{-6} solar masses per year. Such accretion rates can only be maintained for short periods of time, otherwise the nebula would be rapidly depleted in mass making the formation of Jupiter difficult [8].

Secondly, planetesimals must form on timescales of 10^{4-5} years in order to retain a memory of the hot state of the nebula. Longer formation times allow significant inward mixing of non-volatile depleted materials, which would lead to negligible depletion patterns in the planetesimals. These short formation times for the planetesimals would likely lead to the incorporation of live ^{26}Al and ^{60}Fe, which would produce significant amounts of heat in the bodies, and possibly lead to differentiation rather than preservation of nebula products as is seen in chondrites. Additionally, if chondrules formed in the nebula 1-3 million years after CAIs [e.g. 9], it is difficult to understand how this could be achieved if their parent bodies had already formed.

Discussion: It thus appears difficult to reconcile the needed conditions to form MOVE depletion trends from incomplete condensation in an evolving solar nebula with other aspects of solar nebula evolution. This has led us to then look at the dynamical and chemical evolution of the different components of chondrites. The bulk compositions of chondrites are determined by the sum of their components: matrix, chondrules, and refractory inclusions. These components have very different origins and compositions, but all formed directly from dust particles or vapor in the solar nebula and came together in different proportions to form the chondrites. In order to disentangle how these different components achieved their respective compositions, it is necessary to first identify what materials these objects would have been created from.

Here we focus on the materials that were available to form chondrules and matrix, as they are the dominant components of chondritic meteorites. These materials would have formed from materials that were present in the chondrite formation region. The dust located between 2-4 AU, particularly after a million years of disk evolution (when chondrule formation is thought to begin), likely originated at larger heliocentric distances, and therefore cooler temperatures, and would contain the full complement of moderately volatile elements. This material would have been carried inward from larger heliocentric distances by the net advective flows associated with disk evolution and by gas drag. Even dust that was processed in the inner disk and then diffused outwards may have whatever volatiles it lost recondense on its surface as it entered cooler regions as the volatiles in the gas would diffuse outwards as well. This suggests that chondrules and matrix may have initially formed from precursors that had their full inventory of MOVEs, in agreement with Alexander [4]. If these materials became depleted before chondrule formation occurred, it must have been due to *localized* processes, rather than the global scale evolution of the solar nebula.

Summary: We have developed a model that tracks the formation of moderately volatile element depletions in planetesimals in a solar nebula that evolves due to mass and angular momentum transport in agreement with astrophysical models of protoplanetary disks. While the model can produce MOVE depletion trends that are similar to those that are observed in chondritic meteorites, the nebular conditions that are required seem to contradict those that are required by other aspects of solar nebula and chondritic meteorite evolution. Instead, it appears that the precursors to chondritic materials was primitive, unaltered dust that became fractionated in localized thermal events. Such events are expected as they are thought to be responsible for the formation of chondrules, and thus we may be looking at multiple cycles of processing.

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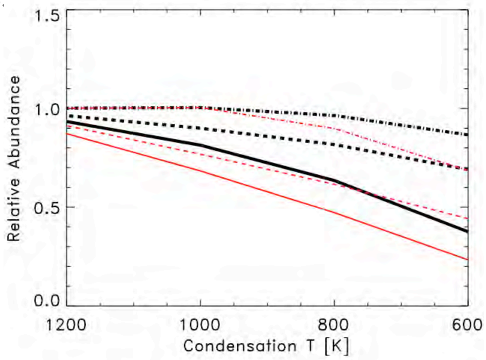

Figure 1: Depletion patterns at 1 AU (solid line), 2 AU (dotted line), and 3 AU (dash-dotted line) for cases where gas drag migration is suppressed (red lines) and where gas drag migration is allowed (black).