# CREATION AND DISTRIBUTION OF CAIS IN THE PROTOPLANETARY NEBULA.

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**Ca-Al rich refractory mineral inclusions (CAIs) found at 1-10% mass fraction in primitive chondrites appear to be several million years older than the dominant (chondrule) components in the same parent bodies. A prevalent concern is that it is difficult to retain CAIs for this long against gas-drag-induced radial drift into the sun. We assess a hot inner (turbulent) nebula context for CAI formation, using analytical models of nebula evolution and particle diffusion. We show that outward radial diffusion in a weakly turbulent nebula can prevent significant numbers of CAI-size particles from being lost into the sun for times of $1 - 3 \times 10^6$ years. To match the CAI abundances quantitatively, we advocate an enhancement of the inner hot nebula in silicate-forming material, due to rapid inward migration of very primitive, silicate-and-carbon rich, meter-sized objects. "Combustion" of the carbon into $CO_2$ would make the CAI formation environment more reduced than solar, as certain observations imply. Abundant $CO_2$ might also play a role in mass-independent chemical fractionation of oxygen isotopes as seen in CAIs and associated primitive, high-temperature condensates.**

We pursue a model in which CAIs form in the inner nebula (0.1 - 2 AU) during an early stage when the region was hot enough to vaporize 95% of all silicates. We do not treat the melting events which affected some CAIs, but merely try to constrain the environment in which these and other CAI evolutionary processes occurred. We envision two different types of region (figure 1): region A, the innermost nebula (perhaps 0.1-0.3 AU), at the outer edge of which CAIs *condense* as precursor vaporized material cools; and region B, somewhat further out (perhaps 0.3-2 AU) which is too hot for ferromagnesian silicates to condense but cool enough for formed CAIs to *survive*, perhaps continuing to react with the gas. Recent nebula models indicate that these radial ranges can sustain the required temperatures for roughly $10^5$ years [1,2].

The dominant ferromagnesian (chondrule) constituents of chondrites apparently formed 1-3 Myr later, when the nebula had cooled significantly [3-5]. The widely noted difficulty with retaining CAIs for this amount of time, against gas-drag-induced drift into the sun, actually refers to a laminar (non-turbulent) nebula [6]. Other studies of turbulent nebulae [7,8] indicate that considerable radial migration is possible for material which is sufficiently well trapped to all turbulent eddies that it diffuses much like gas parcels themselves. The current problem is more complex, because while they are indeed fairly well trapped to the gas and do diffuse as well as gas parcels, CAIs *do* continue to drift inwards slowly at velocity $V_d$, *and* the inner nebula itself is drifting slowly into the sun, at velocity $V_n$, as a result of its own viscous evolution (figure 1).

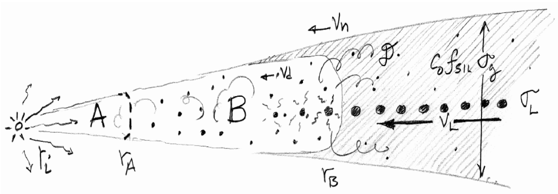

Figure 1: The inner nebula, with gas surface density $\sigma_g(r)$, indicating radial drift ($V_d$) and diffusion ($\mathcal{D}$) of CAIs, gas evolution at velocity $V_n$, and inward radial drift ($V_L$) of meter-sized rubble with mass density $\sigma_L$. Outside of $r_B$ normal silicates are solid, with surface density $C_o\sigma_g$ ($f_{sil} = 1$).

Presuming that CAIs do not exist until they form in the inner solar system, there will be an outward gradient of CAI concentration even if the total silicate mass density has no radial gradient. One can compare the inward radial flux of particles due to gas-drag-induced drift, and nebula drift, with the outward radial flux of particles due to diffusion across this concentration gradient. We assume the nebula diffusivity $\mathcal{D}$ is the same as the more familiar turbulent viscosity $\alpha c H$, with $c$ the sound speed and $H$ the vertical scale height. Then the ratio of the outward mass flux to the inward mass flux is

$$\frac{\mathcal{D}\sigma_g(\partial C/\partial r)}{(V_n + V_d)C\sigma_g} \approx \frac{\mathcal{D}\sigma_g(C/\lambda)}{V_n\sigma_g C} \approx \frac{r}{\lambda}. \tag{1}$$

In the above equation we assume the CAI concentration $C$, relative to the gas, has a radial gradient on scale $\lambda$, and use the facts that $V_n$ and $V_d$ are comparable for mm-sized particles, and that $V_n \approx \mathcal{D}/r$ [9]. Equation 1 implies that outward radial mass flux is larger than inward diffusive flux until the concentration gradient is global in scale - that is, until the tracer material has diffused outwards by a distance larger than $r$.

A new feature of the scenario we advance here is that the entire hot inner nebula region acquires an elevated abundance of heavy elements. This occurs because meter-sized rubble particles, which accrete further out in the nebula, drift *rapidly* inwards at velocity $V_L = \gamma V_K >> V_n$ or $V_d$, where $V_K$ is the Keplerian velocity and $\gamma \sim 2 \times 10^{-3}$ is the ratio of outward pressure gradient force to gravitational force [6,10]. Accretionary models [11] indicate that particles grow readily to meter size even in turbulent nebulae, but further growth is frustrated because they couple to the largest, highest velocity eddies and interparticle collisions occur at sufficiently high velocity to disrupt them. The inward mass flux of this material *into* the hot inner nebula is $2\pi r\sigma_L V_L$. However, rather than "drifting into the sun" as is often assumed, such particles evaporate in the hot inner nebula before reaching the sun, enhancing the vapor phase with their constituents. Once deposited in regions A and B, vaporized material can only be *lost* by slow advection into the sun (at $V_n$) or diffusion outward. Only diffusion can compete with the rapid inward flow of rubble, and then only once a strong concentration gradient is set up by enhancing the concentration in the inner region.

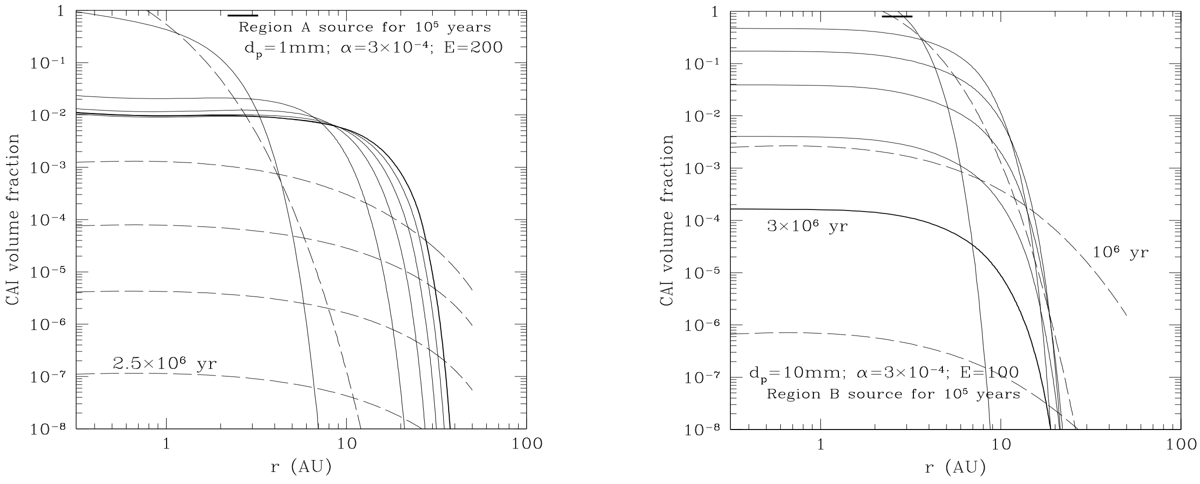

Figure 2: CAI fraction with respect to all silicates *vs.* nebula radius $r$, from $0.5 \times 10^6$ yr to $3 \times 10^6$ yr (thicker lines), in steps of $0.5 \times 10^6$ yr. Solid and dashed curves: nebula models spanning a plausible range of radial viscosity profiles. LEFT: *small* CAIs, and a region A source; RIGHT: *large* CAIs, and a region B source.

Solving a mass balance equation gives us a silicate-material enhancement factor $E$ over solar of approximately:

$$E \sim \frac{\sigma_L V_d}{C_o \sigma_g V_n} \sim \frac{\sigma_L}{C_o \sigma_g} \frac{r V_d}{\mathcal{D}} \sim 40 \frac{\gamma}{\alpha}. \tag{2}$$

In equation (2), we estimate $\sigma_L \sim 10\%$ of all solid material, based on the powerlaw size distributions generated by accretionary models [11-13], and assumed to terminate at 1 meter radius. These powerlaws have roughly equal mass per decade of particle size, so this is a fairly robust approximation.

The composition of these rubble particles is an intriguing aspect of the scenario. In these very early stages, it is likely to be a silicate-carbon mixture similar to materials currently found in comets. These very primitive solids lose their water and more volatile material at $r >> r_B$, but are significantly enriched in carbon, and C/O ratio, relative to CI composition [14]. Thus, when they vaporize at $T > 1500$ K, we suspect that the vapor is *not* enriched in oxygen relative to solar as is the case for vaporization of pure silicates. Rather, the abundant carbon soaks up the oxygen into CO and/or $CO_2$. As the gas cools, CAIs form from a gas more reduced than a nominally solar mix, consistent with the mineralogical evidence [15]. Furthermore, abundant $CO_2$ may lead to mass-independent enrichment of light oxygen isotopes in the gas [16] from which CAIs and associated high-temperature minerals condense [17]. This environment lasts only until the inner nebula cools below the evaporation temperature of silicates and amorphous carbon ($< 10^5$ years), so is restricted to ancient condensates.

To solve the combined drift, advection, and diffusion equations for CAIs in a nebula that is evolving globally over a period of $3 \times 10^6$ years, we employ analytical nebula evolutionary models [18] which span a range of plausible radial viscosity dependencies. The models adopt a disk with initial mass of $0.2 M_\odot$, having the specific angular momentum of the solar system and viscosity sufficient to produce mass influx rates of $10^{-7} - 10^{-8} M_\odot$/yr, typical of T-Tauri stars. We derived Green's functions for the diffusion equation for each of these viscosity dependencies to solve the diffusion part of the solution as a convolution rather than as a full difference equation. The model is described in more detail in [19].

Figure 2 shows sample results for large and small CAIs. Based on their mineralogical properties we are tempted to assign "small" Type A CAIs to region A and "large" Type B CAIs to region B. In all cases, diffusion leads to a nearly radius-independent volume fraction of CAIs, relative to all silicates - for small CAIs, even out to nebula distances where comets form. As time proceeds, the nebula model represented by the dashed lines evolves more quickly to low density than the model represented by the solid lines (a constant viscosity model), so the CAI drift speeds increase and they vanish more quickly for this model type. Also, because their drift velocities are faster, *large* CAIs are lost more quickly in all cases than *small* ones. Thus, a prediction of the model is that CV meteorites, in which large CAIs are more abundant, formed before other types which retain only the longer-lasting small CAIs.

References: [1] Bell, K et al. 1997; Ap.J. 486, 372 [2] Stepinski,T 1998; Icarus 132, 100 [3] Mostefaoui, S et al. 2001; MAPS 37, 421 [4] Huss, G et al. 2001; MAPS 37, 975 [5] Amelin, Y et al. 2002; Science 297, 1678 [6] Weidenschilling, S MNRAS 180, 57 [7] Morfill, G and Völk. H 1984; ApJ 287, 414 [8] Bockelee-Moravan, D et al. 2002; A&A 384, 1107 [9] *e.g.* Lin, D and Papaloizou, J 1985; in *Protostars and Planets II*; Black and Matthews, eds [10] Cuzzi, J et al. 1993; Icarus 106, 102 [11] Weidenschilling, S 1989; in *M. E. S. S.*, Kerridge, ed. [12] Weidenschilling, S 1997; Icarus 127, 290 [13] Weidenschilling, S 2000; Sp. Sci. Rev. 92, 295 [14] Jessberger, E. et al. 1988; Nature 332, 691 [15] Beckett, J. et al. 1988; GCA 52, 1479 [16] Thiemens, M 1996; in *Chondrules and the P-P Disk*, Hewins, Jones, and Scott, eds. (eqns. 11-12) [17] Krot, A et al. 2002; Science 295, 1051 [18] Lynden-Bell, D and Pringle, J 1974; MNRAS 168, 603 [19] Cuzzi, J et al. 2003; in preparation. We gratefully acknowledge recent helpful conversations with G. MacPherson, J. Paque, H. Connolly, and D. Wooden regarding CAIs and cometary IDPs.