Radial distribution of CAIs in the solar nebula.

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Introduction: Widespread evidence exists that calcium-rich, aluminum-rich inclusions (CAIs) were distributed throughout the solar nebula. CAIs formed from minerals condensed at high temperatures achieved only relatively close to the Sun, < 1 au [1,2] CAIs are found in chondrites whose parent bodies, according to isotopic evidence, accreted both inside and outside Jupiter's orbit [3,4], out to at least 3-4 au [2]. CAIs (or their fragments) have been found in the *Stardust* sample return from comet Wild 2. A major open question is how the CAIs were transported beyond Jupiter and to the comet-forming zone.

There are two leading hypotheses for how CAIs were transported to the outer solar system: radial diffusion through the protoplanetary disk [e.g., 2,6-7]; or launching by magnetocentrifgually driven winds < 1 au, falling back on the disk at ~10 au [8-10]. Which mode dominates determines the timing of how CAIs arrive in the carbonaceous chondrite-forming zone beyond Jupiter (~3-4 au). In the disk transport scenario, the earliest-formed CAIs are the first to arrive. In the disk wind scenario, the earliest-formed CAIs would actually be last to arrive, as disk winds are stronger earlier in disk evolution, and would fling CAIs to greater distances in the disk; these CAIs would take longer to radially drift inward than later-formed CAIs. The different scenarios also would imply different distributions of stable isotopic anomalies.

The disk diffusion hypothesis has been modeled and successfully applied to the issue of how CAIs and refractory elements are distributed in the disk [2]. In contrast, the disk wind hypothesis has not been fully tested. Previous models have been proposed in which CAIs both are formed near the Sun and also ejected by magnetocentrifugally driven winds near the magnetospheric truncation radius at ~0.1 au, i.e., "X-winds" [8,9]. These models have been demonstrated not to reproduce the short-lived radionuclide patterns of CAIs, their oxygen fugacities, etc. [12]. Accumulating evidence also shows that magneto-centrifugal outflows in disks are driven from radii ~1 au, rather than ~0.1 au [13]. Setting aside the issue of how CAIs form, it remains to be tested whether CAIs can be launched by disk winds and transported to the outer solar nebula. We test that hypothesis here.

For CAIs to have formed at < 1 au and end up in the ~10 au region, several criteria must be satisfied. First, CAIs must be found high enough above the disk midplane that they may participate in the magneto-centrifugal outflow. Second, they must overcome gravity and be accelerated in the outflow, to speeds sufficient to reach 10 au. Third, they must not exceed escape velocity or remain bound to the gas in the outflow, or else they will not fall back onto the disk. Below we examine each condition in turn.

Vertical distribution of CAIs: CAIs larger than ~1 mm in size are likely to settle to the midplane and not participate in a disk wind. All particles naturally settle themselves to the disk midplane due to the vertical component of the gravity from the central star. In general, the density $\rho_{\rm CAI}(z)$ of CAIs must be $\rho_{\rm CAI}(z) = \rho_{\rm CAI}(z)\ \exp(-z^2/2H_{\rm CAI}^2)$, where z is the height above the disk midplane. The gas density is $\rho(z) = \rho(0)\ \exp(-z^2/2H^2)$, where $H=C/\Omega$ is the gas scale height, C being the sound speed and Ω being the Keplerian orbital frequency. If CAIs were very small, like dust, and uniformly mixed with the gas, they would have a scale height $H_{\rm CAI} = H$, and their concentration relative to gas would everywhere be $\rho_{\rm CAI}(z)/\rho(z) = \Sigma_{\rm CAI}/\Sigma$, the ratio of the column densities. In general, though, $H_{\rm CAI} = H\ x\ (1+x^2)^{-1/2}$, where $x = 0.80\ [\alpha/\Omega t_{\rm stop}]^{1/2}$, where α is the turbulence parameter, $t_{\rm stop} = \rho_s\ a\ /\ (\rho(0)C)$ is the stopping time at the disk midplane, ρ_s is the CAI mineral density, and a is the CAI radius [Eq. 39 of 14]. At 1 au, we estimate $\alpha \approx 3 \times 10^{-4}$, $\rho(0) \approx 10^{-9}$ g cm^{-3}, $C \approx 1 \times 10^5$ cm s^{-1} [2], finding for a~1 mm, $t_{\rm stop} = 3000$ s, $x = 0.33$, $H_{\rm CAI} = 0.31\ H$. CAIs are vertically distributed with a scale height only 1/3 the scale height of the gas.

For this set of parameters, the concentration of CAIs near the midplane would be increased to $\rho_{\rm CAI}(z)/\rho(z) = 3.2\ \Sigma_{\rm CAI}/\Sigma$, but their concentration above the midplane would be considerably reduced. At just $z = 1\ H$, the gas density is a factor 0.61 lower than the midplane value; but at the same location, $z = 3.2\ H_{\rm CAI}$, and the CAI density is 0.055 lower than the midplane density, and $\rho_{\rm CAI}(z)/\rho(z) = 0.029\ \Sigma_{\rm CAI}/\Sigma$. At $z = 2\ H$, $\rho_{\rm CAI}(z)/\rho(z) \approx 2 \times 10^{-8}\ \Sigma_{\rm CAI}/\Sigma$, while at $z = 3\ H$, $\rho_{\rm CAI}(z)/\rho(z) \sim 10^{-18}\ \Sigma_{\rm CAI}/\Sigma$. Even for CAIs with radii 300 μm, $H_{\rm CAI} = 0.51\ H$, and at $z = 3\ H$, $\rho_{\rm CAI}(z)/\rho(z) \sim$ ~$10^{-5}\ \Sigma_{\rm CAI}/\Sigma$. Only a very small fraction of CAIs with radii 300 μm, and essentially **no** CAIs with radii of 1 mm could exist just 3 gas scale heights above the midplane at 1 au. Even fewer larger CAIs would reside at these heights, or in gas of lower density.

These considerations matter because all models of disk winds and magnetocentrifugal outflows show that gas is not launched away from the disk except at several disk scale heights H above the disk midplane

[15-17]. In particular, $v_z > 10^3$ cm/s only at heights $z > 3H$, where virtually no CAIs of radii 1 mm could reside. We conclude that only CAIs with radii < 300 μm (the precise number depending on the turbulence parameter α, among other factors) are even at $z > 3H$ to find themselves in a disk wind in the first place. The large ~1 cm CAIs found in CV chondrites could not be launched at all unless $\alpha > \text{few} \times 10^{-3}$.

Launching of CAIs: Smaller CAIs with radii a~100 μm that do find themselves at $z > 3H$ can be launched by disk winds, but only if the drag force acting on them can overcome the gravitational force. Unlike gas, which is ionized and feels a direct magnetic force in a magnetocentrifugal flow, particles are accelerated only by the drag force with the gas. The downward force is $m\Omega^2 z$, where the mass $m=(4\pi\rho_s\, a^3/3)$. The drag force (in the Epstein regime) felt by the particles as they settle at speed Δv relative to the gas is $2.1\ \pi a^2 \rho\ C\ \Delta v$, where ρ is the gas density and C the sound speed [18]. The speed at which particles settle therefore is $\Delta v \sim 0.63\ (\rho_s/\rho)\ a\ \Omega\ (z/H)$. Assuming smaller CAIs with a~100 μm and conditions at 1 au, $\rho \approx (10^{-9}\ \mathrm{g\ cm^{-3}})\ \exp(-z^2/2H^2)$, we find $\Delta v \sim 0.01\ \mathrm{km\ s^{-1}}$ at $z=3H$, and $\Delta v \sim 0.45\ \mathrm{km\ s^{-1}}$ at $z=4H$. These are to be compared to the gas velocities at these heights, which are $v_z \ll 0.1\ \mathrm{km\ s^{-1}}$ at $z < 4H$ [Fig. 5 of 17]. In general, launch velocities do not exceed the sound speed ~1 km $\mathrm{s^{-1}}$, and then only above 4 scale heights, where gas densities are very low and CAIs can fall back to the disk. Particles with radii a~10 μm, see $\Delta v \sim 0.05\ \mathrm{km\ s^{-1}}$ at $z=4H$, and just avoid falling back to the midplane. Therefore, we conclude that only CAIs with radii < 10 μm are launched by disk winds.

Launch velocity of CAIs: Assuming CAIs are small enough to exist at $z > 3\ H$ and also feel a stronger drag force than gravitational force, so they can be launched, it remains to be shown that they would not achieve sufficient velocities to escape the solar system. Gas is accelerated by the magnetic fields in a magnetocentrifugal outflow, eventually to speeds of tens of km/s relative to the background Keplerian flow, so that it escapes the disk in a jet. Particles in the wind also feel a drag force accelerating them upward and outward. During this stage, neglecting gravity, the equation of motion for each component of the CAI's velocity is $dv/dt = (v_{\rm gas} - v)/t_{\rm stop}$, with $t_{\rm stop} \sim (1.6 C\rho/\rho_s\ a)^{-1}$. Before they are launched high above the disk, the stopping time is much shorter than the timescale over which particles see conditions change, which is the dynamical timescale $\sim (H\ /\ v_z) \sim \Omega^{-1}$. Particles match the gas velocity. Eventually the particles reach heights above the midplane where the gas density is so low that the aerodynamic stopping time is much longer than the dynamical time, and particles' velocities cease to change. Thus, particles end up with the velocity of gas where the gas density is $\rho \sim 0.6\ \rho_s\ a\ \Omega\ /\ C$. For particles with radii of 10 μm, that density is 4×10^{-15} g $\mathrm{cm^{-3}}$, which is achieved at $z = 8H$ for a midplane density of $1 \times 10^{-9}\ \mathrm{g\ cm^{-3}}$ [Fig. 5 of 17]. At that height, the gas velocities are $v_r \approx 3.5$ km/s, $v_\varphi \approx v_K + 2$ km/s, and $v_z \approx 3.5$ km/s, where $v_K \approx 30$ km/s is the Keplerian velocity. Thus particles with radii 10 um achieve heliocentric velocities 32.4 km/s before they cease to be accelerated. Particles with radii ~1 μm would be accelerated until gas densities dropped to $\rho \sim 4 \times 10^{-16}$ g $\mathrm{cm^{-3}}$, which we estimate would take place at z~12H, where the heliocentric velocity would be ~37 km/s. These are not significant launch velocities: at most, 10 μm particles could be launched from 1 au to only 1.4 au, and 1 μm particles from 1 au to only 3 au.

Conclusions: CAIs must be found in the disk at $z > 3\ H$ just to be in the region where gas is launched. Only those with radii < 100 μm will be found this high above the disk midplane. CAIs also must be small enough to be pushed upward by the disk wind faster than they fall back to the disk midplane. Only CAIs with radii < 10 μm will do so. Even CAIs that are launched by the wind will cease to be accelerated once they have risen a few disk scale heights, where gas velocities are lower. Only CAIs with radii < 1 μm have a chance of being accelerated long enough to reach distances > 10 au. Most CAIs are much larger than this [19]. It does not seem possible for disk winds to launch the large (~1 cm) CAIs found in CV chondrites [19] to the carbonaceous chondrite-forming zone > 3 au.

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