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The distributions and ages of refractory objects in the solar nebula

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ABSTRACT

Refractory objects such as Calcium, Aluminum-rich Inclusions, Amoeboid Olivine Aggregates, and crystalline silicates, are found in primitive bodies throughout our Solar System. It is believed that these objects formed in the hot, inner solar nebula and were redistributed during the mass and angular momentum transport that took place during its early evolution. The ages of these objects thus offer possible clues about the timing and duration of this transport. Here we study how the dynamics of these refractory objects in the evolving solar nebula affected the age distribution of the grains that were available to be incorporated into planetesimals throughout the Solar System. It is found that while the high temperatures and conditions needed to form these refractory objects may have persisted for millions of years, it is those objects that formed in the first 10^5 years that dominate (make up over 90%) those that survive throughout most of the nebula. This is due to two effects: (1) the largest numbers of refractory grains are formed at this time period, as the disk is rapidly drained of mass during subsequent evolution and (2) the initially rapid spreading of the disk due to angular momentum transport helps preserve this early generation of grains as opposed to later generations. This implies that most refractory objects found in meteorites and comets formed in the first 10^5 years after the nebula formed. As these objects contained live ^{26}Al, this constrains the time when short-lived radionuclides were introduced to the Solar System to no later than 10^5 years after the nebula formed. Further, this implies that the $t = 0$ as defined by meteoritic materials represents at most, the instant when the solar nebula finished accreting significant amounts of materials from its parent molecular cloud.

1. Introduction

Among the most primitive objects found in our Solar System are the so called refractory inclusions, which formed at high temperatures within the solar nebula. These objects are generally classified into two types: the Calcium, Aluminum-rich Inclusions (CAIs) and Amoeboid Olivine Aggregates (AOAs). The CAIs, as their name implies, are composed primarily of Ca and Al-bearing minerals. Among them are corundum, hibonite, anorthite, spinel, and perovskite, which are the same minerals expected to first condense or become stable in a gas of solar composition (Grossman, 1972; MacPherson, 2005). The AOAs, which contain forsterite and Fe–Ni metal, which are the next stable condensates to form in that same gas along with many of the minerals found in CAIs, are similar in mineralogy to rims that are found around some CAIs. These similarities suggest that these objects are coeval, possibly forming close to one another in space and time (see recent review by Krot et al. (2009)).

CAIs and AOAs have been identified in nearly all classes of chondritic meteorites, though the abundances and properties of these refractory objects vary among the different groups (Scott and Krot, 2005; Scott, 2007). For example, CAIs and AOAs are most abundant in CV and CO chondrites as they make up as much as ~10% of the volume of a given meteorite. The CVs also contain the largest CAIs, with sizes typically ranging from 0.1 to 1 cm in diameter. Much smaller refractory objects, with different mineralogy and textures have also been found, such as the hibonite-rich inclusions in CM chondrites measuring tens to hundreds of microns across (Liu et al., 2009). Small CAIs and AOA-like particles have also been identified in the materials collected by the STARDUST spacecraft from Comet Wild 2 (Brownlee et al., 2006; Zolensky et al., 2006; McKeegan et al., 2006; Messenger et al., 2008). Thus high temperature materials were common components of primitive bodies that formed throughout the Solar System.

Refractory objects have long been of interest because of they are thought to provide clues about some of the hottest environments to have existed within the solar nebula. The minerals found in CAIs are stable at temperatures above the condensation point for forsterite under canonical nebular conditions, while AOAs contain those minerals predicted to exist right around the temperature at which forsterite condenses (Grossman, 1972; MacPherson, 2005; Krot et al., 2009). The specific temperature at which forsterite condenses in a gas of solar composition depends on the ambient pressure. Cassen (1994) suggested a value around 1350 K is a good guide, with the expectation being that it is accurate within 50–100 K. Further, refractory objects, in particular the CAIs, are of

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interest as they have the oldest ages of all the materials that have been dated in our meteorite collections (Amelin et al., 2002, 2009; Bizzarro et al., 2004; Kita et al., 2005), and as such define the age of the Solar System. All other events in the formation and early evolution of the Solar System are given in reference to the ages of these objects (e.g., Kleine et al., 2009). Given these properties, refractory objects are thought to record information about the hottest, earliest environments of our solar nebula.

Recently, efforts have been made to gain further insight into the timing of the formation of refractory objects and what they can tell us about processes and conditions that were present within the solar nebula. For example high-precision measurements of ^{26}Mg excesses have allowed estimates to be made of the duration of CAI formation. These studies have largely focused on the large CAIs from CV chondrites (Thrane et al., 2006; Young et al., 2005; Jacobsen et al., 2008), though CR CAIs have also been studied (Makide et al., 2009). Estimates for this duration range from as small as 20,000 years (Thrane et al., 2006; Jacobsen et al., 2008) to 0.3–0.5 Myr (Young et al., 2005; Makide et al., 2009). The specific meaning of this duration is still a matter of debate, but Makide et al. (2009) define it as the time period between when the first CAI precursors were processed in the solar nebula and when the CAI formation region cooled to the point that forsterite began to condense ($T \sim 1350$ K).

Information on how long CAIs were formed, and thus how long temperatures in excess of $\sim$1350 K were maintained in the solar nebula would provide important constraints for models of its structure and evolution. For example, reaching the temperatures necessary to form refractory objects in the solar nebula requires an additional source energy beyond irradiation from the central star. One possible source of energy is internal dissipation of the type predicted in a viscous protoplanetary disk, such as that invoked to explain the accretion of mass from a protoplanetary disk onto its central star (e.g., Lynden-Bell and Pringle, 1974; Ruden and Pollack, 1991; Hartmann et al., 1998). Thus the duration of CAI formation could constrain the time when high temperatures existed, and thus the rates of mass and angular momentum transport that occurred in the solar nebula.

An important aspect of the story of refractory objects, however, is that they experienced significant dynamical evolution within the solar nebula prior to their incorporation into the bodies in which they are found. That is, if CAIs and AOAs began their formation in regions of the nebula that were at or above the forsterite condensation temperature (Makide et al., 2009), such temperatures would be limited to at most the inner 2 AU of the nebula, with inside of 1 AU being most likely for reasonable choices of parameters (D'Alessio et al., 2005). In order for such grains to be incorporated into comets, they would have to be transported to the cold outer regions of the solar nebula where such objects are thought to form. For example, Comet Wild 2 is thought to have reached its final mass outside of 20 AU (Brownlee et al., 2006).

Further, outward transport of some sort is also needed to explain the preservation of refractory objects in the solar nebula after their formation and prior to their incorporation into chondritic meteorite parent bodies. That is, ^{26}Al and Pb–Pb ages of chondrules indicate that they are 2–5 million years younger than the CAIs with which they co-accreted (Amelin et al., 2002, 2009; Bizzarro et al., 2004; Kita et al., 2005; Scott, 2007). This age difference has proven to be a challenge to dynamical models of small bodies in the solar nebula, as in the absence of an outward transport mechanisms, CAIs are expected to be lost from the solar nebula on much shorter timescales. This loss would be due to the outward radial pressure gradient expected within the solar nebula, with hot, dense gas near the Sun and cold, sparse gas further away, partially supporting the gas against the force of gravity from the Sun. As a result, the gas orbited the Sun at velocities slightly below those of a Keplerian orbits. Solid bodies thus had their motions impeded by the gas, and lost energy and angular momentum to the gas, spiraling inwards over time (Adachi et al., 1976; Weidenschilling, 1977; Cuzzi and Weidenschilling, 2006). The inward drift velocity of solids was a strong function of the size of the solids being considered, but 0.1–1 cm sized objects, such as the large CAIs, would have drift inwards at rates of $\sim$1–10 cm/s. Thus CAIs would drift inward from 2 AU (the inner edge of the asteroid belt) to the inner edge of the disk in as little as $\sim 10^5$ years.

Two primary models have been invoked to explain how CAIs were not only preserved for this time period, but also how they were redistributed throughout the nebula to be incorporated into primitive bodies. The first is the X-wind model (Shu et al., 1996), in which part of the material pushed towards the star during protoplanetary disk evolution was launched upwards from the disk in strong winds driven by magnetic interactions between the Sun and the inner edge of the nebula. Solids could have been entrained in these winds, and pushed upwards and outwards, falling back onto the nebula at different locations. Unfortunately, as reviewed by Krot et al. (2009), the predictions of the X-wind model appear to be inconsistent with the properties of primitive materials.

The second type of model to explain the preservation and redistribution of refractory inclusions are disk models, which tap into the mass and angular momentum transport that occurred during the final stages of the formation of the Sun. Cuzzi et al. (2003) demonstrated that in a viscously evolving solar nebula, turbulence within the disk would combine with the large-scale flows of the disk to carry CAIs outward against the inward motions associated with gas drag, helping to preserve them for extended periods of time. Boss (2008) showed that the gaseous motions associated with mass and angular momentum transport arising due to spiral arms in a marginally gravitationally unstable solar nebula may also preserve CAIs, as materials from the inner part of the disk could be transported outwards distances of $\sim$20 AU on short timescales ($\sim 10^3$ years).

An important aspect of these CAI preservation models is that the dynamical evolution of CAIs, and thus their paths through the solar nebula and the efficiency with which they are retained, are strong functions of their size. That is, the larger CAIs will drift inwards more rapidly due to gas drag than their smaller counterparts, meaning the larger CAIs would not be preserved as efficiently. Thus we must begin to wonder if the differences in dynamics may play a role in setting the inferred ages and/or formation duration of the CAIs. For example, given that so many CAIs are expected to be lost from the solar nebula due to gas drag, are the measured ages of CAIs expected to represent the entire time period where temperatures were high enough for such objects to form, or just a fraction of it? Since large CAIs would be lost from the nebula more readily than small ones, do we expect different ages or spread in ages for CAIs of different sizes? How do the ages of CAIs delivered to the comet formation region compare to those that were available to be accreted by the chondrite parent bodies? The answers to these questions will help us better interpret what the distribution and ages of refractory grains tell us about the evolution of the solar nebula.

In this paper, the dynamics of refractory objects are studied in the context of a young protoplanetary disk evolving under the influence of mass and angular momentum transport – similar to what has been inferred to be operating in disks around other stars $<10^6$ years old (e.g., Sicilia-Aguilar et al., 2006). The goal here is not to explain distinguishing characteristics of the different types of refractory objects. Rather, the focus is on understanding how the ages of the CAIs, and by extension the other refractory objects that formed at or around the region where forsterite condensed in the solar nebula, vary as a function of time and location as a result of their dynamical evolution. In the next section, the model used to describe the evolution of the solar nebula and the radial redistribution of refractory grains is presented. Results of this model are then compared to previous studies and discussed in the context of inferred CAI ages and formation durations within the literature. The main conclusions are summarized and suggestions for future work then discussed.

2. Protoplanetary disk and transport model

In order to understand the dynamics of refractory objects, it is important to understand the setting in which they formed. Protoplanetary disks, such as those thought to serve as analogs for our own solar nebula, evolve over time as mass is transported inward and accreted onto the central star in its last stages of pre-main sequence evolution. To compensate for this mass flow, the disk expands as angular momentum is transported outward (see recent review by Dullemond et al. (2007)). Associated with this evolution is the dissipation of orbital energy of the gas which leads to heating of the disk. If mass transport is rapid enough, much higher temperatures can be reached than would be achieved from irradiation from the central star alone. The temperatures that can be reached depend on the rate of mass transport, but for rates of 10^{-6}–10^{-7} $M_{\odot}$/year, which can be achieved for very young solar-mass stars, temperatures >1350 K are expected inside of 1 AU (D'Alessio et al., 2005; see their Fig. 1). Thus, it is at these accretion rates that regions of the nebula, beyond the very inner edge, would reach temperatures that exceed the condensation point of forsterite, and where CAIs and AOAs, or their precursors, would be most easily produced.

The driving force for mass and angular momentum transport in protoplanetary disks remains the subject of ongoing study. Nonetheless, it is thought that the long-term evolution of the disk can be described by assigning a viscosity to the gas, where the differential rotation of the gaseous fluid gives rise to stresses which are what control the rates of mass and angular momentum transport (Shakura and Sunyaev, 1973; Lynden-Bell and Pringle, 1974; Ruden and Pollack, 1991; Hartmann et al., 1998; Boley et al., 2006). Here we adopt the traditional α-viscosity formalism to describe the evolution of the disk (where the viscosity, ν, is given by αcH, where c is the local speed of sound and H the local disk scale height) without specifying a source for the viscosity. The goal here is to look at the general effects of disk evolution.

The global evolution of a viscous disk surface is calculated by solving the equation:

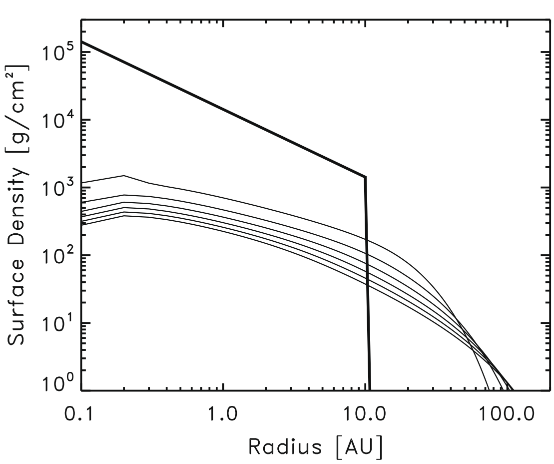

Fig. 1. The initial surface density of the disk in the Base Model (heavy line) and the surface density of the disk at 5×10^5 year time intervals up to $t = 3 \times 10^6$ years.

$$\frac{\partial \Sigma}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(r\Sigma v_r) = 0 \tag{1}$$

where Σ is the surface of density at a given heliocentric distance, r, from the central star and v_r is the vertically averaged radial velocity of the gas given by:

$$v_r = -\frac{3}{\Sigma r^{\frac{1}{2}}}\frac{\partial}{\partial r}\left(r^{\frac{1}{2}}\Sigma \nu\right) \tag{2}$$

The temperature of the disk midplane, which determines the values of c and H $(= c/\Omega)$, used to determine the viscosity are found by Ciesla and Dullemond (2010):

$$T_m^4 \sim T_{irr}^4 + \frac{3}{8}\kappa\Sigma T_{visc}^4 \tag{3}$$

Here T_{visc} is the temperature of the disk surface due to viscous dissipation, given by:

$$2\sigma T_{visc}^4 = \frac{9}{4}\nu\Sigma\Omega^2 \tag{4}$$

and T_{irr} is the temperature of the disk due to irradiation:

$$2\sigma T_{irr}^4 = \frac{2\phi L_*}{4\pi r^2} \tag{5}$$

where ϕ is the angle between the stellar radiation and the disk surface (taken to be $\phi = 0.05$) and L_* is the luminosity of the protostar, taken to be:

$$L_* = 4\pi R_* \sigma T_*^4 \tag{6}$$

Here it is assumed that $R_* = 2.5R_{\odot}$ and $T_* = 4000$ K. More complicated functions of T_{irr} could be used, but for the purpose of this paper a simple estimate suffices.

An opacity of $\kappa = 5$ cm^2/g is adopted throughout the region of the disk with temperatures below 1350 K for simplicity (Cassen, 1994). At higher temperatures, a linear combination of 5 cm^2/g and 0.1 cm^2/g, the assumed opacity where Mg- and Fe-bearing solids are absent, is used to determine the net opacity as done by Cassen (1994).

As mass and angular momentum are transported through the disk, the gas will push the small solids suspended within it, redistributing them as a result of its evolution. How solids are affected by the gas is quantified by the Stokes number, St, which is the ratio of the stopping time to the overturn time of the largest eddy in the disk, where $t_s = a\rho/\rho_g c$ is the stopping time with a being the particle radius, ρ the particle density, and ρ_g the local gas density at the midplane, and the overturn time of the largest eddy is Ω^{-1} with Ω taken to be the Keplerian orbital frequency $(GM_{\odot}/r^3)^{\frac{1}{2}}$.

How a column of refractory grains, with a surface density of Σ_{rg}, evolves within a viscously evolving disk is described by (Garaud, 2007):

$$\frac{\partial \Sigma_{rg}}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(r\Sigma_{rg}u_r) = \frac{\partial}{\partial r}\left[r\nu\Sigma\frac{\partial}{\partial r}\left(\frac{\Sigma_{rg}}{\Sigma}\right)\right] \tag{7}$$

where u_r is the net radial velocity of the particles given by the sum of that due to the large-scale flows associated with disk evolution (Eq. (2)) and that due to gas drag. Note here it is assumed that the particle diffusivity is equal to the viscosity, though this may not necessarily be the case (e.g., Johansen et al., 2006). It is also assumed that $St \ll 1$, such that the diffusivity is independent of the Stokes number, an assumption that is valid except under the most extreme (when $St > 1$) conditions for the cases considered here (Cuzzi and Weidenschilling, 2006; Youdin and Lithwick, 2007). The gas drag velocities are assumed to be given by Cuzzi et al. (2003), Cuzzi and Weidenschilling (2006):

$$V_{gd} = 2St\frac{1}{\rho_g\Omega}\frac{\partial P}{\partial r} \tag{8}$$

The way in which the model is run is as follows. The initial surface density profile of the disk is assumed to have the form $\Sigma(r) = \Sigma_0(r/1\text{ AU})^{-p}$. A value of α is then specified, and the evolution of the disk is calculated on a radial grid ranging from 0.05 AU to $\sim$6000 AU. The grid spacing is small in the inner regions of the disk ($\Delta r = 0.1$ AU at $r < 5$ AU, increasing in size by a factor of 1.05 at each sequential grid point). Refractory grains of a specified size, or their precursors, are assumed to form wherever the temperature exceeds 1350 K, and in those regions the refractory grain surface density is defined as $\Sigma_{rg} = 2.5 \times 10^{-4}\Sigma$, where the numerical factor represents the fact that the typical solid to gas mass ratio for solids in the gas is 0.005, and 5% of those condensibles are what would be expected to make up the precursors of CAIs (Cuzzi et al., 2003). Note, this means that there is no enhancement in the CAI "factory," an issue that is discussed further below. At lower temperatures, the surface density of refractory grains is found by calculating the combined effects of the viscous spreading of the disk and gas drag as given in Eq. (7). Solids that migrate into regions with $T > 1350$ K are destroyed and replaced with new ones. When temperatures at the inner edge of the disk drop below 1350 K, the refractory grains are allowed to fall through the inner boundary of the grid, and are assumed to be lost to the Sun (inside of 0.05 AU in this model).

In order to track the distribution of the refractory grains of different ages, a number of different grain epochs are tracked in a given model run. That is, for each model run, the refractory grains that are produced in the regions where $T_m > 1350$ K are divided into 10^5 year batches, meaning that those that form at $0 < t < 10^5$ years are tracked as one collection, those that form at 10^5 years $< t < 2 \times 10^5$ years by another, and so on. In some cases discussed below, an even finer temporal resolution was employed.

3. Model results

3.1. The Base Model

An example of a model run, which is taken as the "Base Model" is shown in Figs. 1–7. After discussing the results of this particular model, we explore how the results change with different choices of model parameters. The parameters for this particular model are such that the disk begins with a structure given by $\Sigma(r) = 14,200(r/\text{AU})^{-1}$ g/cm^2 between 0.1 and 10 AU (giving an initial disk mass of $\sim$0.1 $M_\odot$), and a value of $\alpha = 10^{-3}$ is assumed for the turbulence parameter. An outer disk edge of 10 AU is chosen to represent the distance inward of which all molecular cloud material would fall during the formation of the star and disk. This outer radius is found as in Dullemond et al. (2006) by equating the maximum specific angular momentum of a molecular cloud with the angular momentum of the material in Keplerian orbit around the central star. For a solar mass cloud the radius would be given by $R_c = GM_\odot/c^2$, with c being the speed of sound within the cloud. The cloud was assumed to be rotating at a uniform, constant rotation rate of $\Omega_c = 10^{-14}$ s^{-1}. Assuming a molecular cloud temperature of 15 K, this suggests all the material would fall within $\sim$10 AU of the young star. It is worth noting that disks with similar initial masses and outer radii had been studied by Cassen (1996, 2001) as a means of explaining some of the chemical properties of chondritic meteorites.

Fig. 1 shows the evolution of the surface density of the disk, with each line representing time intervals of 500,000 years from the initial state, which itself is indicated by the thick black line. Over time, mass is lost from the disk as it is accreted onto the star, resulting in the drop in surface density throughout most of the disk. The mass loss is accompanied by outward transport of angular momentum, which can be seen as the radial extent of the disk increases with time. Much of this transport occurs during the earliest stages of disk evolution as material migrates to $\sim$100 AU in the first 500,000 years.

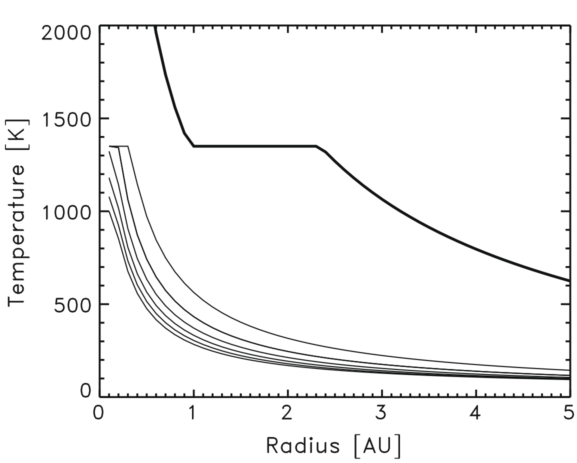

Fig. 2. The early thermal structure of the inner disk in the Base Model. The early temperature profile of the disk is given by the heavy black line, while the temperature of the disk at 5×10^5 year time intervals are shown up to $t = 3 \times 10^6$ years. Temperatures in excess of 1350 K, when refractory grains are assumed to form, persist for nearly $t = 1.5 \times 10^6$ years.

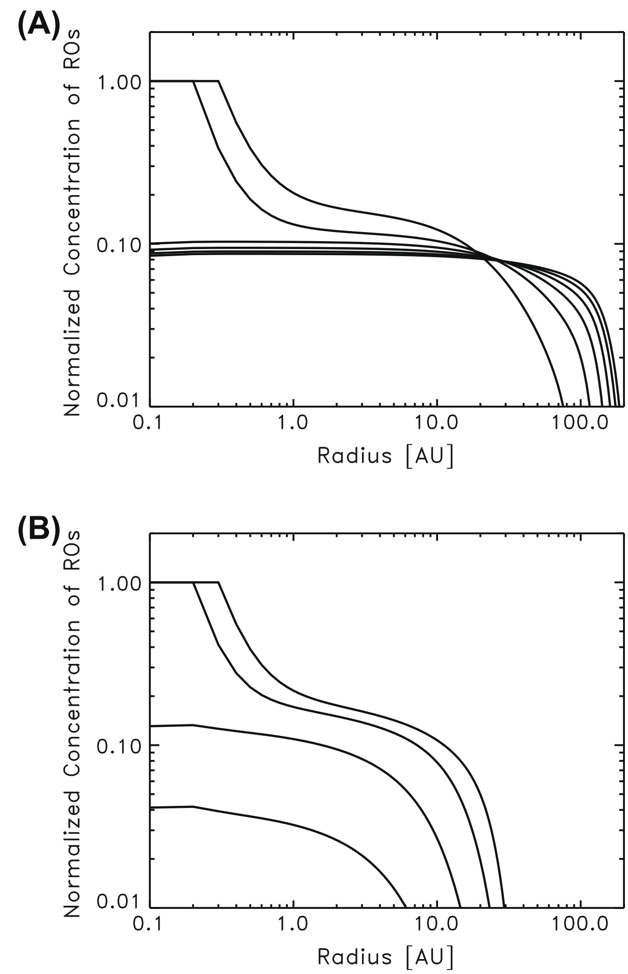

Fig. 3. The spatial distribution of fine refractory objects (ROs) in the disk for fine-grained objects (5 μm in diameter, Panel A) and millimeter-sized objects (Panel B). Plotted are the normalized concentrations – the ratio of the surface densities of the refractory objects to the gas, divided by the value expected in a gas of solar composition (2.5×10^{-4}). Each line shows the distribution at 5×10^5 year intervals.

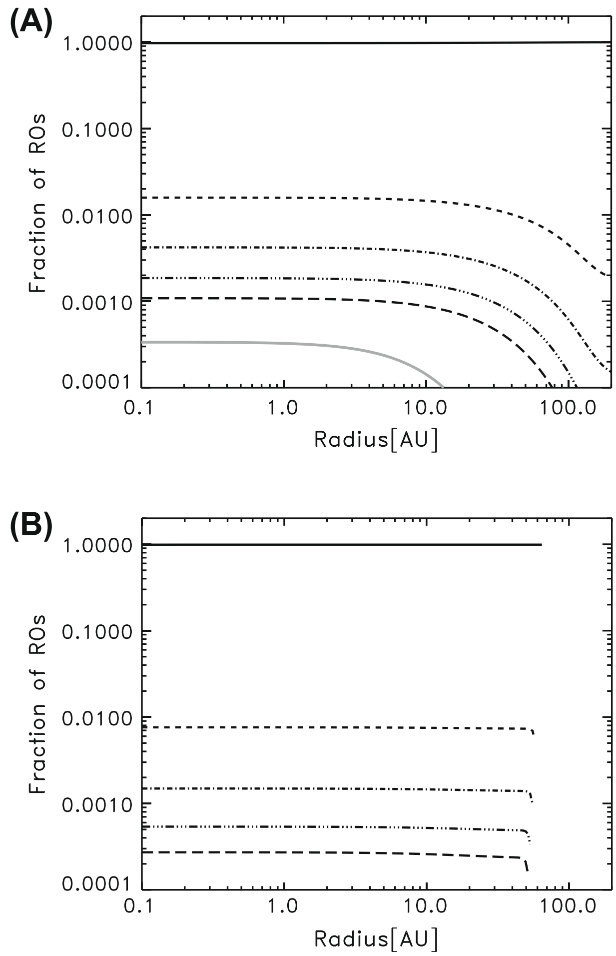

Fig. 4. The fractions of surviving fine-grained refractory objects throughout the disk at each location in the disk after 2×10^6 years of disk evolution for the fine-grained refractory objects (Panel A) and the millimeter-sized objects (Panel B). The black solid line shows those objects that formed in the first 10^5 years of disk evolution, the short dashed line shows those that formed at $10^5 < t < 2 \times 10^5$, the dot-dash line those that formed at $2 \times 10^5 < t < 3 \times 10^5$, the dot-dot-dot-dash line those that formed at $3 \times 10^5 < t < 4 \times 10^5$ and the long dashed line those that formed at $4 \times 10^5 < t < 5 \times 10^5$. The gray, solid line indicates those that formed at $t > 10^6$ years.

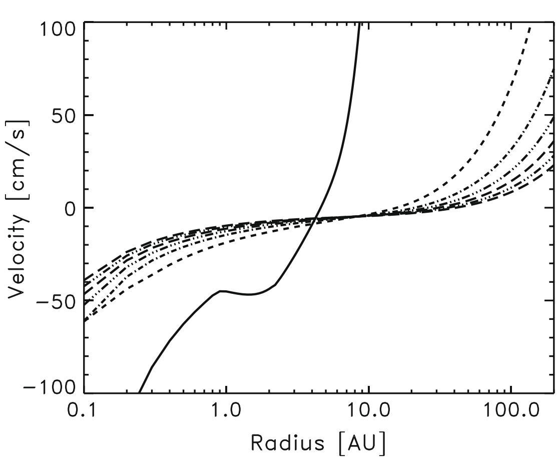

Fig. 5. The net advective velocities of the gas in the disk for the Base Model during the inital stages of evolution (solid line) at $t = 5 \times 10^5$ year intervals.

Fig. 2 shows the thermal evolution of the inner disk at the same 500,000 year intervals. As in Fig. 1, the thermal state very early in the model is shown in the thick black line, and the disk becomes

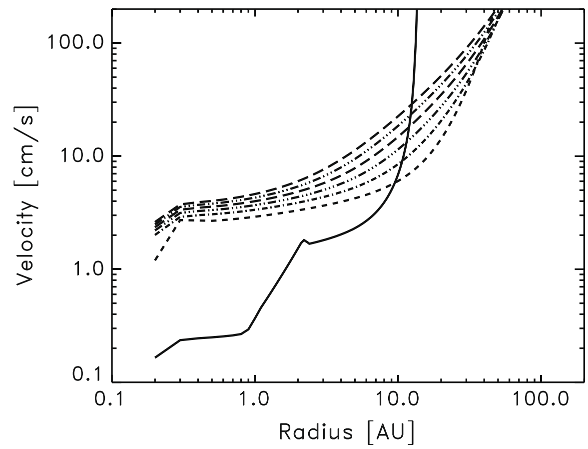

Fig. 6. The gas drag velocities (directed inward) of the millimeter-sized particles in the disk in the Base Model at the same times shown in Fig. 5.

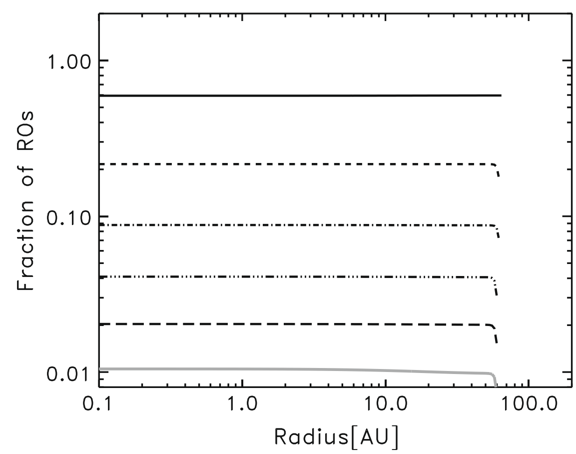

Fig. 7. The fractions of surviving millimeter diameter refractory grains after 2×10^6 years in the Base Model that formed in the first 10^4 years of disk evolution (black solid line), at $10^4 < t < 2 \times 10^4$ (short dash), at $2 \times 10^4 < t < 3 \times 10^4$ (dot-dash), at $3 \times 10^4 < t < 4 \times 10^4$ (dot-dot-dot-dash), and at $4 \times 10^4 < t < 5 \times 10^4$ (long dash) and at $t > 10^5$ years (gray solid).

progressively cooler with time. Initially, temperatures above 1350 K exist beyond 2 AU from the Sun. The temperature plateau at 1350 K is due to the change in opacity assumed to occur at this temperature as ferromagnesium silicates, which are the primary source of opacity, evaporate/condense approximately at this temperature (e.g., Cassen, 1994). This leads to a roughly isothermal cavity at the disk midplane of the type seen here (Cassen, 2001). The disk rapidly cools over time as the surface density drops, lowering both the rate of energy released by viscous dissipation (Eq. (4)) and the optical depth of the disk which allows radiation to escape more easily (Eq. (3)). Thus after 5×10^5 years, the Refractory Object Factory (ROF) extends only to ~0.3 AU. Progressive cooling is seen as the $T = 1350$ K isotherm migrates to the inner edge of the disk, but remains outside of 0.1 AU for >10^6 years. Thus refractory objects can potentially be produced for an extended period of time in this disk, much greater than the estimated duration of CAI formation based on ^{26}Al chronology of CAIs.

Fig. 3 shows how refractory objects, fine-grained objects measuring ~5 μm diameter (Panel A) and larger objects measuring 1 mm diameter (Panel B), are redistributed through the disk over 3×10^6 years at 5×10^5 years intervals. The fine-grained dust modeled here is comparable in size to those refractory objects seen in CM chondrites (e.g., Liu et al., 2009) and the materials that were collected from Comet Wild 2 by the STARDUST mission, while the millimeter-sized objects are comparable in size to the CAIs found in CV chondrites (MacPherson, 2005; Hezel et al., 2008), which define the age of our Solar System (and thus our $t = 0$ for when discussing meteorites). Specifically, what is shown is the normalized concentration of these objects where the concentration is defined as the ratio of the surface density of the refractory objects to the surface density of the gas, and this ratio is divided by the canonical value in the ROF of 2.5×10^{-4}.

Refractory objects are formed for the first $\sim 10^6$ years in the disk, and are then subjected to transport from the large-scale flows associated with disk evolution, diffusion, and gas drag migration, with the latter being negligible for the fine-grained materials. The fine-grained materials become relatively uniformly distributed throughout the nebula after 10^6 years, with a normalized concentration of $\sim$0.1 nearly everywhere inside of 100 AU at later times. As gas drag is negligible for such grains, this can be used as a proxy for the gas as well, meaning that $\sim$10% of the gas present in the disk at these times once resided in a region where temperatures exceeded 1350 K. The millimeter objects are not transported as far outward in the disk as the fine-grained materials because gas drag offsets their outward motions. Further, once the disk cools to the point that the refractory objects are no longer produced, these larger grains rapidly migrate inwards and are lost from the disk, such that the normalized concentration in the disk is less than 0.01 after 2×10^6 years.

Fig. 4 shows how the ages of the refractory objects vary with location after 2×10^6 years of disk evolution. In each of these panels, the fraction of surviving grains that formed at a given time are plotted as a function of location in the disk, with each line representing a different population of refractory grains formed at 10^5 years intervals. That is, the fraction of refractory grains remaining in the disk that formed in the first 10^5 years is shown in the solid line, the fraction that formed during 10^5 years $< t < 2 \times 10^5$ years are shown in the short dashed lines, and so on. As can be seen, throughout all the disk, the refractory objects that formed in the first 10^5 years dominate the population of refractory grains in the disk for both sizes. Similar behavior is seen at all times of disk evolution, with those objects formed in the first 10^5 years dominating the population everywhere in the disk. The exception is the very innermost regions of the disks immediately outside the ROF, as some objects are able to diffuse outwards from their source region. Here, the abundances of these newly formed objects can exceed the abundances of the earlier generations. However, this is limited to a small radial distance, as the abundance of these grains drops off rapidly further away from the source region. This is also a short-lived situation, as once the refractory objects are no longer produced, they are quickly lost to the central star or diluted within the rest of the disk, as indicated by the dominance of the older objects even at these small heliocentric distances.

The dominance of the objects formed during the earliest stages of disk evolution is due to two effects. Firstly, the rate of production of refractory objects is largest during the first 10^5 years of disk evolution. As viscous evolution continuously drains mass from the disk, it is at the earliest epochs when the largest amount of material is available from which refractory objects can be produced. Further, temperatures are also at their highest at this point, meaning that the ROF occupies the largest volume it will at any point in disk history (Fig. 2). At later times, the volume of the ROF continuously declines as does the amount of mass it contains, thus leading to fewer and fewer refractory objects being produced.

Secondly, the dynamical evolution of the disk works to preserve the oldest objects. That is, refractory objects are lost if they fall onto the star as part of the accretion of material through the disk or under the influence of gas drag, and are lost or reset when they enter regions at small heliocentric distances with temperatures above 1350 K. Thus those objects that are most likely to survive for long periods of time are those that get transported outward to the greatest degree. This is most easily done early in the evolution of the disk when the rates of mass and angular momentum transport are highest.

This is demonstrated in Fig. 5, which shows the net velocity of the gas and fine dust as a function of distance from the star at 5×10^5 years time intervals. During the earliest times, velocities are greatest in magnitude, as mass and angular momentum transport are at their highest levels. Initially, velocities in the inner disk, inside of $\sim$4 AU, are negative, indicating the net flow is inward, towards the star. Beyond this point, the velocities are positive, indicating a net outward flow away from the star. These outward flows cause the disk to expand with time, pushing gas and small solids to larger heliocentric distances. Newly formed refractory objects will initially be subjected to inward flows as they form at small heliocentric distances, which make outward transport difficult. However, because temperatures are high during this stage, the diffusivity of particles will be large enough such that some will be able to diffuse outward the short distance needed to reach the regions where the net velocity is directed outwards. Once those particles are able to do so, their outward movement is aided by the radial expansion of the disk, allowing them to be carried outward very large distances.

While the velocities of the inward flows decrease in magnitude with time, as shown in Fig. 5, the radial distance over which they are directed grows with time. That is, after 5×10^5 years the net flows are directed inwards everywhere inside of $\sim$10 AU, with the stagnation point continuing to migrate outwards with time. Thus refractory grains produced later in disk evolution must diffuse outwards much greater distances in order to make it to the regions where the flows are directed outwards. The time for a particle to diffuse a given distance goes as the square of the distance ($t_{diff} \sim r^2/\nu$ here), meaning that even though the inward flows of the disk have decreased in magnitude, they are subjected to these flows for much longer times before reaching a point in the disk where the flows would aid their survival. This is generally a losing battle, and as such, objects formed at later times are less likely to survive for longer periods of time within the solar nebula.

For comparison, Fig. 6 shows the inward drift velocities of the millimeter-sized objects at different times in disk evolution. Again, this inward drift offsets the outward transport of the refractory objects, though at early stages, outward diffusion and the outward directed flow of the gas is able to overcome this and still allows objects to be carried far outside the ROF. However, the inward drift of particles at rates of >10 cm/s outside of 10 AU in the disk (corresponding to a inward drift rate of 10 AU per 5×10^5 years) prevents these objects from being carried beyond $\sim$20 AU to any significant level throughout the lifetime of the disk.

It is worth noting here that the millimeter-sized refractory objects that survive after 10^6 years are largely concentrated at small heliocentric distances, as gas drag limits their outward movement and later begins depleting them from the outer disk. This means that of those planetesimals that form after 10^6 years, only those that formed in the inner nebula would contain refractory objects such as these. However, those forming after 2×10^6 years would contain few, if any such objects, regardless of where they formed. Comets and planetesimals from the outer solar nebula could only contain such objects if they accreted in the first few hundred thousand years of nebular evolution. On the other hand, small grains are distributed throughout the disk at these later times.

As it is those objects from the first 10^5 years that dominate the population, a second run was performed for the millimeter-sized objects in the Base Model, but with a finer time resolution such that batches of objects formed in 10,000 year intervals were tracked. As recent estimates for the duration of CAI formation are on the order of 20,000 years, it is instructive to also consider this fine time resolution and to compare it to the meteoritic record. The results are shown in Fig. 7, which indicates the formation time of objects remaining in the disk after 2 million years. Those refractory objects that formed in the first 10,000 years make up $\sim$60% of the refractory grains surviving in the disk, while those that formed between 10,000 and 20,000 years make up over 20% of those survivors. Thus, those refractory inclusions that formed in the first 20,000 years would by far be the primary survivors in the disk, and be the objects most likely to be analyzed from meteorites.

The concentrations of large refractory grains at $t > 10^6$ years found in this model are much too small to explain the observed abundances of CAIs in CV chondrites (which contain $\sim$1–5% CAIs by volume (Scott and Krot, 2005; Hezel et al., 2008)). Note that a value of 5% corresponds roughly to a normalized concentration of 1 here. The low abundances found here demonstrate the challenge that gas drag represents to the preservation of large refractory objects. Cuzzi et al. (2003) suggested that turbulent diffusion in a viscously spreading disk of the type considered here could preserve enough CAIs in the nebula to explain the observed fractions in chondritic meteorites provided that the CAI factory was enhanced in CAI-forming materials by factors of 20–5000. Similar enhancements would increase the abundances of refractory objects in the asteroid belt region of the disks in these models to the levels needed to produce the observed abundances of CAIs in CV chondrites, despite slightly different treatments in the production and dynamics of the gas and solids. These differences are due to slightly different assumptions in the models, and are discussed in greater detail below.

3.2. Varying parameters

Unfortunately, the exact conditions that existed during the formation of the Solar System are unknown, which means that there is significant uncertainty in the values of different parameters that used in the model presented here. Further, observations of young stellar clusters indicate that the properties of young stars and their disks vary significantly, suggesting a wide range of values is possible for any given parameter. As such, it is necessary to evaluate how the specific results of the model depend on these parameters. Below we discuss how the specific results of the model depend on the free parameters in the model, with specific examples shown to illustrate the points. A summary of how the model depends on the key parameters is listed in Table 1.

3.2.1. The turbulence parameter, α

The role of α in this model is to define the viscosity and diffusivity of the disk. Fig. 8 shows the evolution of a disk with the same initial conditions as the "Base Model", but with a lower value of $\alpha = 10^{-4}$. Because of the lower value of α, the disk does not evolve as rapidly, allowing the disk to retain a greater amount of material for longer than the Base Model. This also allows the disk to maintain a temperature of 1350 K near the star for a longer period of time. As a result, refractory objects are produced for as long as $\sim 2 \times 10^6$ years in the disk, though mainly at the very inner edge, $r \sim 0.1$ AU, for much of this time. These objects migrate outwards under the same dynamical processes described above, though the lower viscosity and diffusivity means that the these processes generally operate more slowly. However, because the disk does not lose mass as quickly, the Stokes number for the millimeter-sized particles does not rise as rapidly as in the Base Model, keeping the gas drag velocities lower than what is shown in Fig. 6.

For both sized particles, the normalized concentration in the disk outward of 1 AU is much less than found in the Base Model. There are two factors that play into this. Firstly, with the lower level of turbulence, the viscosity is less than in the Base Model, meaning viscous dissipation does not produce as much heat. As a result, the radial extent of the ROF is much less than in the Base Model, extending to just $\sim$1.5 AU, rather than $\sim$2.5 AU early on. Thus the amount of material processed at a given time is reduced. Also, this means that particles must diffuse outwards a greater distance than in the Base Model in order to reach the region where the net flow of material is away from the star (this location is relatively unaffected by the change in the value of α). Since turbulent diffusion is reduced due to the lower value of α, this outward transport is more difficult than in the Base Model and fewer particles reach the region of outward flow and thus fewer survive.

Despite the lower abundance of refractory objects in the disk, the population of survivors is again dominated by those that formed at the earliest stages of disk evolution. This is again due to the larger number of objects formed at this stage and the dynamics of the disk during its early evolution aiding the outward transport of those objects. Subsequent populations have more difficulty surviving, so even though a smaller number of objects from that initial population survive in the disk, they still dominate the overall inventory.

Higher values of α allow for greater stresses and viscous dissipation. Higher values thus allow for larger ROFs and greater outward flows and diffusion of the refractory objects. For small refractory grains, such a situation results in a higher normalized concentration throughout the disk. However, for the larger objects, the rapid evolution of the disk generally proves more challenging in terms of

Table 1
The effects of changing a single parameter or property of the disk model used here on the overall evolution and preservation of refractory objects.

Parameter/ property	Change	Effect
α	Increase	Higher temperatures throughout disk More rapid loss of gas Larger concentration of small ROs throughout disk Large ROs lost in shorter time
	Decrease	Lower temperatures throughout disk Less outward diffusion Lower concentration of small ROs All ROs confined to smaller heliocentric distance
p	Increase	Higher fraction of material starts at $T > 1350$ K More rapid loss of gas Higher concentration of small ROs throughout the disk Large ROs lost in shorter time
	Decrease	Less materials processed at $T > 1350$ K Net outward velocities located further from $T > 1350$ K Lower concentration of all ROs
Outer disk radius	Increase	Lower temperatures throughout disk Less materials processed at $T > 1350$ K Net outward velocities located further from $T > 1350$ K Lower concentration of all ROs
	Decrease	Higher fraction of material starts at $T > 1350$ K More rapid loss of gas Higher concentration of small ROs throughout the disk Large ROs lost in shorter time
Disk mass	Increase	Higher temperatures throughout disk Higher fraction of material starts at $T > 1350$ K Larger concentration of all ROs throughout disk
	Decrease	Lower temperatures throughout disk Less materials processed at $T > 1350$ K Lower concentration of all ROs

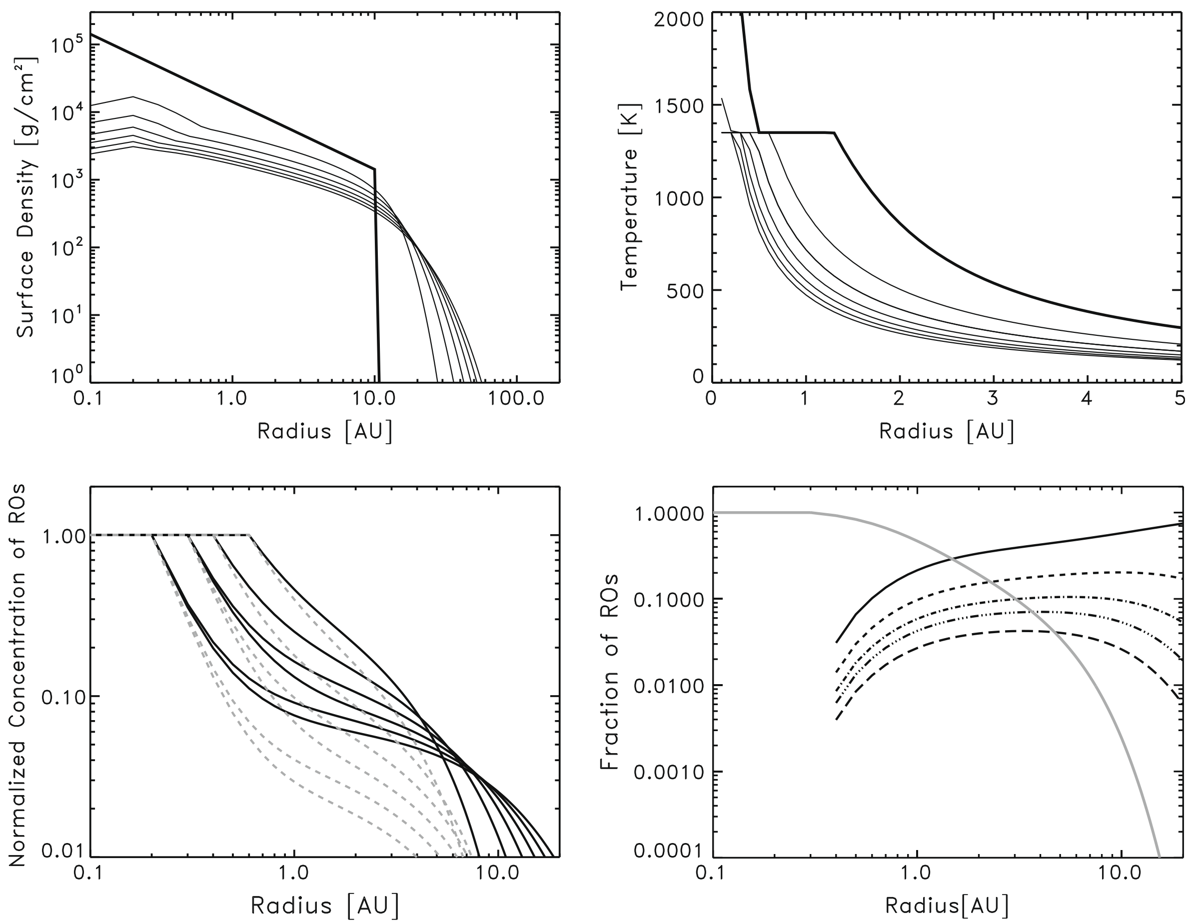

Fig. 8. The results of a disk model with the same initial structure as the Base Model but evolving with $\alpha = 10^{-4}$. The surface density and temperature throughout the disk are shown at 5×10^5 year intervals, as are the normalized concentrations of the fine-grained refractory objects (black, solid line) and the millimeter-sized objects (gray, dashed line). The age distribution of the fine-grained objects after 2×10^6 years is also shown, with the lines representing the same formation intervals as in Fig. 4. The age distributions of the millimeter-sized objects are found to be nearly identical to that of the fine-grained objects.

preservation for long timescales. Because of the high viscosity, mass is lost from the disk at a greater rate, and what remains is spread over a larger area. This results in higher Stokes numbers, and thus, correspondingly higher inward drift rates. This makes preservation of CV-like CAIs difficult in such models. For example, using the conditions of the "Base Model" presented above, but with $\alpha = 10^{-2}$, the larger objects are lost from the disk in less than 10^6 years.

3.2.2. The surface density distribution

Fig. 9 shows the results of a model where the disk surface density falls of as r^{-2}, though the total mass of the disk remained as $0.1\,M_{\odot}$. A value of $\alpha = 10^{-4}$ was assumed. Because the mass of the disk was concentrated at smaller heliocentric distances, much of it was lost to the star on shorter timescales than in the case of $p = 1$. Despite the change in surface density profile, the radial extent of the ROF is comparable in the two cases, but because of the steeper density distribution here, a higher fraction of the disk being exposed to high temperatures. This results in a concentration of fine refractory objects exceeding 25% throughout most of the disk for much of its evolution. Again, this is a good proxy for the fraction of gas that is exposed to temperatures in excess of 1350 K.

The normalized concentration of the millimeter-sized grains is greater here than in the $p = 1$ case as well. This is due to two effects. Firstly, the steeper surface density profile can provide a larger outward velocity of the gas as it evolves, since the outward velocity would increase for more negative values of $\partial\Sigma/\partial r$ (Eq. (2)). This helps to offset the inward motions from gas drag more effectively. Secondly, because a larger fraction of the disk starts out within the ROF, the millimeter-sized grains are not diluted as much by unprocessed materials from the cooler, outer part of the disk. This is true even with the inward offsets that arise from gas drag migration.

As with the previous models considered here, the largest population of survivors in the disk continue to be those that formed during the very earliest stages of disk evolution. Even with refractory grains still being produced in the disk after 2×10^6 years, those that formed in the first 10^5 years of disk evolution make up over 90% of the survivors outside of 1 AU.

Similar runs were performed with values of α of 10^{-3} and 10^{-2}. Due to the higher viscosity in these runs, the ROF extended even further out into the disk and thus exposed a higher fraction to the disk to these high temperatures. As a result, a large population of refractory grains were produced. However, due to the high viscosity and the fact that much of the disk mass was concentrated at its inner edge, the gas densities in the disk dropped more rapidly than in those models which assumed a similar structure as the Base Model. This proved to be a problem for retention of the millimeter-sized objects, as the lower gas densities led to higher Stokes numbers and more rapid radial drift via gas drag. As a result, very few objects were retained for times beyond 10^6 years.

Runs were also performed with the mass of the disk initially spread out to 50 AU, as might be expected if the Solar System formed from a molecular cloud with more angular momentum.

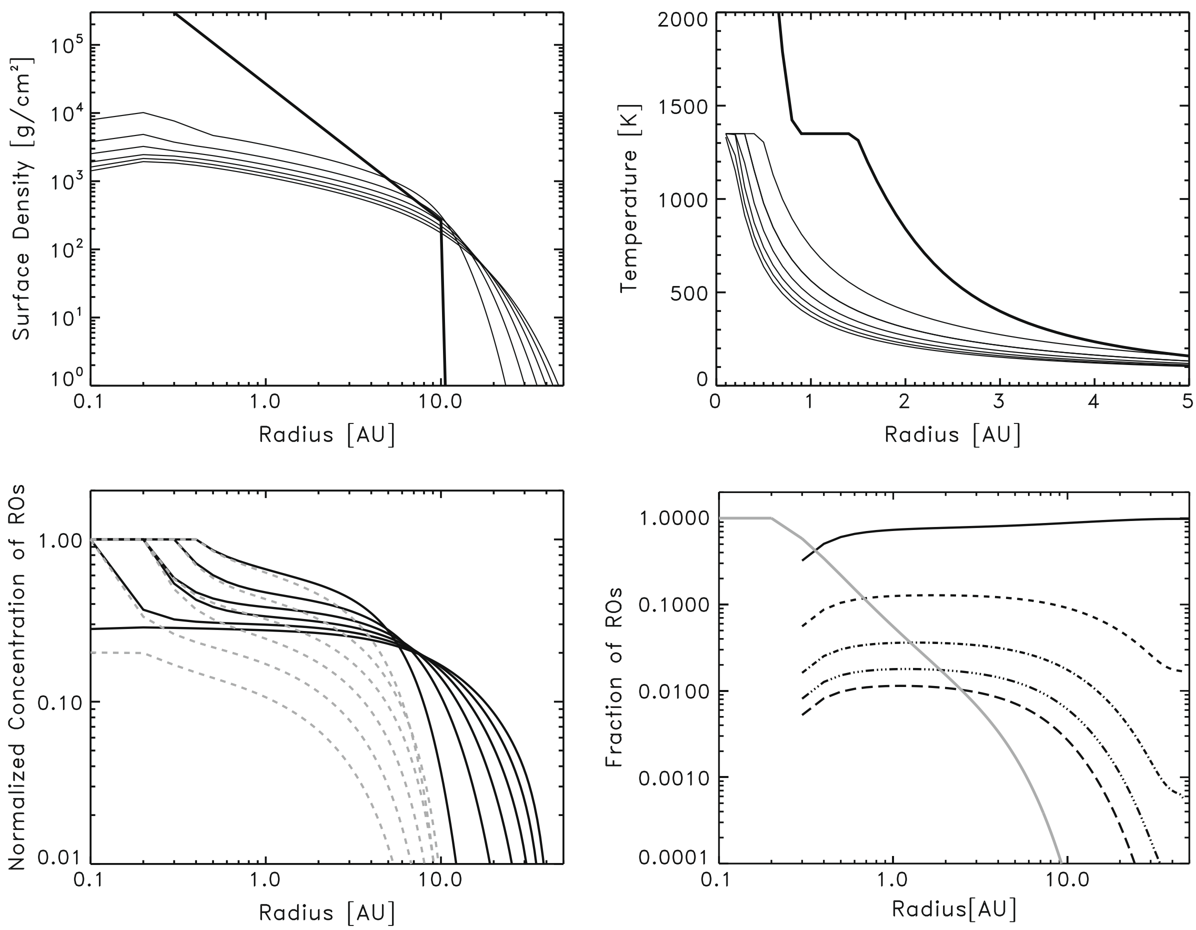

Fig. 9. The results of a disk model with the same overall mass as the Base Model, but with a surface density distribution that falls off as r^{-2}, and with $\alpha = 10^{-4}$. The plots are the same as those described in Fig. 8. Again, the age distributions of the millimeter-sized objects are found to be nearly identical to that of the fine-grained objects.

In such cases the volume of the ROF was smaller and contained less mass than considered above, as the rates of viscous dissipation and the optical depth of the disk decrease with decreasing surface density. As a result, the concentration of refractory objects was less than shown in the cases above. Further, the stagnation point in the disk was located further out the disk, as more material was located at larger heliocentric distances and thus able to drive materials inward more efficiently. Such disks proved to be very poor at retaining refractory objects for long periods of time, though those that did survive continued to be dominated by the earliest generation.

4. A closer look at CAI preservation

As discussed above, one of the primary reasons for considering the long-term dynamical evolution of large (>1 mm) refractory objects, such as CAIs, is that the reported age difference between them and the chondrules that they accreted with is greater than the expected time it would take such objects to drift to the inner edge of the disk under the influence of gas drag. Thus some process must have operated either to offset this drift or to push CAIs to larger heliocentric distances such that they would have much longer to travel before being lost to the Sun.

Outward transport of the type considered here, where diffusion and the radial expansion of a viscous protoplanetary disk carry grains outwards tens to hundreds of AU may succeed in helping to preserve CAIs for the required time period. This was first demonstrated in Cuzzi et al. (2003), where these effects were considered and it was shown that some amount of CAIs are kept in the solar nebula for timescales of millions of years. However, the abundances of the CAIs relative to the gas at these late times were generally very small, particularly for the large, CV-like CAIs, such that the predicted abundances in planetesimals would be much lower than what is observed. The results of this study support that conclusion. To compensate for this, Cuzzi et al. (2003) suggested that the inward drift of solids could enhance the ROF in the raw materials needed to form these objects, and would thus produce a larger number of objects such that, while only a small percentage of them remain in the disk at late times, the overall concentration of these objects relative to the gas would be larger.

Cuzzi et al. (2003) estimated the volume fraction of CAIs in a given meteorite parent body, f, by taking their calculated value for the concentration of CAIs relative to the gas, C_{CAI} and plugging it into the formula:

$$f = \frac{C_{CAI}}{C_{CAI} + 0.005} \tag{9}$$

where 0.005 represents the canonical ratio of solids to gas in the disk. For the CAIs that were millimeters to centimeters in size, enhancements in the CAI factory of 20–5000 were needed to produce the observed abundances of CAIs in CV chondrites (1–5% by volume).

For the cases considered here, enhancements comparable to the low-end of those estimated by Cuzzi et al. (2003) would suffice to preserve the proper number of large refractory objects, with values of ∼5–30 being all that is necessary to give. Similar enhancements would also increase the abundances of refractory objects into the levels that the abundances of CAIs to be incorporated into planetesimals in the 2–4 AU region of the nebula after 1–2 million years after their formation in the models presented here. Large enhancements may be difficult to achieve due to the finite amount of material that could be brought inwards from the outer disk as discussed in Ciesla and Cuzzi (2006), though this study focused on water enhancements inside the snowline, and not silicates inside the forsterite evaporation front, so it remains to be seen how limiting this effect may be. Nonetheless, enhancements of more than 100 are likely difficult to achieve.

However there are other factors that may play a role in determining the abundances of refractory objects that get incorporated into a planetesimal when it forms beyond that explicitly considered here. For example, when estimating the abundance of materials in a planetesimal, it is likely that planetesimal sampled only a finite volume of the nebula when it formed, and records the compositions of the materials in that volume, rather than the average values of a more extended region. Thus far, the discussion has focused on the variation in the column density of refractory grains evolves within the disk. However, it is not necessarily the column density that is the critical factor to look at when estimating what the abundance of a given species would be within a planetesimal that forms at a given time and location within the solar nebula. That is, planetesimals form at, or around, the midplane of the solar nebula, and thus it is necessary to determine the abundances of the CAIs at that location.

As mentioned above, as the gas density of the disk diminishes, its effective strength at pushing the CAIs around, as quantified by the Stokes number also decreases. Thus, CAIs will settle to the midplane more efficiently and rapidly as St increases. If there is a weak level of turbulence present in the disk, either naturally or induced by the settling of solids which leads to a dense particle layer that results in shear instabilities (e.g., Cuzzi et al., 1993), then the distance over which the CAIs will be distributed can be characterized by a thickness, H_{CAI}. If we assume that the turbulence is characterized by the value of α, then $H_{CAI} \sim \sqrt{\frac{\alpha}{St}}H$ provided $\alpha < St < 1$ (Cuzzi and Weidenschilling, 2006). Thus, the volume density of the gas and CAIs would be $\rho_g \sim \Sigma/2H$ and $\rho_{CAI} \sim \Sigma_{CAI}/2H_{CAI}$, respectively. This means that the ratio of volume mass densities of CAIs to gas would be

$$\frac{\rho_{CAI}}{\rho_g} = \frac{\Sigma_{CAI}}{\Sigma}\sqrt{\frac{St}{\alpha}} \tag{10}$$

(Cuzzi and Weidenschilling, 2006). For example, for values of $\alpha = 10^{-4}$ and $St = 0.01$, which are plausible values for the level of turbulence and Stokes number of millimeter-sized objects in the late stages of disk evolution, the volume abundance of CAIs at the disk midplane relative to the gas volume abundance would be $10\times$ the ratio of surface densities. Lower values of α would lead to even greater enhancements. Such low values of α are expected at the midplane of the inner parts of MRI-active disks due to the low ionization levels and weak coupling to magnetic fields (e.g., Oishi and Mac Low, 2009). Further, it has been suggested that turbulence in protoplanetary disks may produce lower levels of diffusivity, or a lower effective α, in the vertical direction (perpendicular to the midplane) than in the radial direction (Johansen et al., 2006). As it is the vertical diffusivity that is important in determining the level of settling that grains would experience, this suggests it is possible for radial transport of the type studied here to occur while at the same time, enhanced abundances of larger grains develop at the disk midplane than would previously expected.

In order for planetesimals to record the abundances of the refractory grains at or around the disk midplane, planetesimal formation would have to occur in a way such that planetesimals are preferentially born from materials that have collected within that region. Models from Cuzzi et al. (2001, 2008) and Johansen et al. (2007) argue that this would be the case, as planetesimals form due to gravitational instabilities arising from concentrations of particles as a result of turbulence. Formation at or around the midplane would be the most efficient as this is the region containing the highest mass of solids. Planetesimals formed in these models would represent snapshots of the materials present in a finite volume of the disk. Further, the models of Cuzzi et al. (2001, 2008) suggest that planetesimals would preferentially form from particles of a given size, meaning that the aerodynamic processes may concentrate large refractory grains to even greater levels than have been calculated.

This differs from the planetesimal formation scenarios proposed in Weidenschilling (1997) who suggested that planetesimals form from incremental accretion, where growth begins at high altitudes and continues as particles settle toward the midplane, sweeping up materials along the way. Were planetesimal growth to occur in this manner, the resulting bodies would likely record conditions through the entire vertical column of the disk, with the final abundances of refractory grains being closer to the value predicted by looking at the surface densities of materials rather than the values predicted around the disk midplane. Thus, formation of planetesimals in a weakly turbulent disk may help explain the higher abundances of large CAIs in CV chondrites than would be otherwise expected. Settling alone can increase the concentration of larger objects by factors up to $\sim$10–30 – this is comparable to the values needed in the cases presented here to increase the abundances of large refractory objects around the disk midplane to the level needed to explain the observed abundances in CV chondrites.

Alternative ways of explaining the survival of these grains have been suggested. It is possible that the diffusivity of materials in the disk is greater than the viscosity by a factor of a few (Pavlyuchenkov and Dullemond, 2007), allowing materials to diffuse outwards greater distances than found here, giving them a greater distance to travel inwards before being lost from the disk. A second possibility is that the structure of the refractory grains may deviate from perfect spheres, effectively reducing the Stokes number for the particles and the rates at which they drift inwards through the disk. The structures of the Fluffy Type A CAIs suggest that such structures are possible (MacPherson, 2005). Finally, it is possible that the mass and angular momentum transport through the disk occurs very rapidly during the first few 10^4–10^5 years of disk evolution (Boley et al., 2006; Boss, 2008), slowing down to a more quiescent state afterwards. Since the disk would not be losing mass as rapidly, the high gas densities would lead to slower inward drift rates of the refractory grains, increasing their lifetimes in the disk. Further, the more quiescent state would allow larger solids, such as the big CAIs found in CV chondrites, to settle to the midplane more effectively, increasing their concentrations relative to the fine dust at the disk midplane, exactly where planetesimal formation is expected to occur. Each of these possibilities should be investigated in greater detail.

5. Discussion and summary

This study has focused on understanding how the dynamics of gas and dust affects the distribution of ages of the refractory objects that would be made available to be incorporated into planetesimals throughout a protoplanetary disk. This was specifically motivated by recent reports that the spread in CAI ages may not be more than $\sim$20,000 years (Thrane et al., 2006; Jacobsen et al., 2008). This date has been interpreted as the duration over which CAIs, and by extension, all refractory objects, would have formed. For example, Wood (2004) actually considered what the tight clustering of ages of CAIs meant as preliminary results of these dating studies began to emerge. Recognizing that the brief duration of CAI formation, taken as 0.5 Myr in his study, was short compared to the expected lifetime of the solar nebula, Wood (2004) argued that such objects must have predated the protoplanetary disk epoch, or specifically the classical T-Tauri phase (Class II phase) of its evolution, as it is expected to last 10^6—10^7 years (Feigelson and Montmerle, 1999). Instead, recognizing that the infall stage of the molecular cloud or the evolved protostar phase (Class 0 or Class I), which are expected to last on the order of 10^4 and 10^5 years respectively (Feigelson and Montmerle, 1999). Wood (2004) suggested that the CAIs formed during these earliest stages of star and disk formation.

However, the estimated duration of CAI formation largely comes from studies of the larger CAIs found in CV chondrites, and implicitly assumes that the dynamical evolution of the refractory objects in the solar nebula was not a factor in determining the ages and duration of when such objects would have formed. Here it was shown that it is possible for the temperatures needed to produce refractory objects (in excess of 1350 K) to exist within the disk for periods of >10^6 years while still producing a population of refractory objects whose measured ages would suggest a formation period of 10^4–10^5 years. That is, the tight distribution of ages of CAIs reported in recent studies would not necessarily reflect the duration of CAI formation, but rather this clustering of formation times is a natural product of the dynamical evolution of a protoplanetary disk and the solids within it. This dynamical evolution favors the survival of a large number of objects formed at the earliest stages of disk evolution. Those that formed later either make up a tiny fraction of the survivors or do not survive within the disk for significant portions of the disk lifetime.

More specifically, with refractory objects forming in the disk when temperatures exceed 1350 K, and at an abundance of $\Sigma_{rg} = \Sigma/4000$, the time when the largest number of refractory objects will be produced is at the very initial stages of disk evolution. At this point the disk is most massive and temperatures highest, such that the ROF encompasses the largest amount of mass. As the disk evolves, the mass of the disk decreases and the temperatures decline, decreasing the rate of production of such objects. Thus the later-forming objects are less numerous than those formed during the early evolution of the disk.

Further, the dynamical evolution of the disk favors the survival of the earliest formed objects. As a disk expands as part of its viscous evolution, the gas carries refractory objects to larger heliocentric distances. This occurs most rapidly during the early evolution of the disk when mass and angular momentum transport rates are highest. Over time, the net motions of materials become inward throughout much of the disk, making outward transport from the inner disk, or survival for long periods of time, more and more difficult. This is particularly true for larger objects where gas drag becomes an important part of their dynamic evolution – the lower gas densities in the disk at later times generally lead to more rapid inward velocities (higher Stokes numbers). Thus those objects that form later are redistributed throughout the rest of the disk at a lower efficiency than the earlier generation.

These results are found to be robust as different disk structures and evolutionary parameters were considered for completeness. In each case, the population of refractory objects at a given location in the disk was dominated by those that formed during the earliest epoch of disk formation. The only locations where the oldest objects did not dominate the population were immediately outside the ROF. This was generally limited to inside of a few tenths of an AU, and the very earliest stages of disk evolution. At later times, such as during the time period that chondritic meteorite parent bodies formed, the oldest objects dominated, even at the inner boundary of the disk.

Given that it is the oldest refractory objects that will be preserved within the solar nebula, the >10^6 years age difference between CAIs and chondrules (Amelin et al., 2002; Kita et al., 2005) can be understood. Chondrules are the products of transient heating events within the solar nebula, and their ages are reflective of their last melting event. Following Makide et al. (2009), the CAIs on the other hand are dating the time when they entered a region of the nebula where forsterite was able to condense from the gas. Those objects which record this time period are going to have very old ages, based on the models presented here, regardless of when chondrule formation took place. If meteorites contain chondrules that formed >10^6 years into disk evolution, the refractory inclusions they accrete with are going to have this very old age regardless.

That surviving refractory objects will be dominated by those that formed during the very earliest stages of disk evolution has implications for beyond the ages of objects in chondritic meteorites. The high temperature materials contained in comets are thought to have originated in the inner solar nebula and were then transported to the outer regions through processes such as those described here (Nuth et al., 2000; Wooden, 2008). These grains likely formed in the first $\sim 10^5$ years of nebular evolution as well, otherwise they would not have been transported out to the comet formation region. Such early transport would allow the grains to avoid the complications of bypassing the forming Jupiter and Saturn that they would encounter if their transport occurred at later times.

Further, as it is those refractory grains formed during the first 10^4–10^5 years of disk evolution that dominate the population seen in meteorites and comets, this places constraints on the timing for isotopic homogenization or modification of primitive materials. For example, at what stage of evolution short-lived radionuclides were delivered to the Solar System remains a matter of debate, with possibilities including a supernova injecting materials into the parent molecular cloud and triggering its collapse (e.g., Boss et al., 2008), continuous enrichment of the parent molecular cloud by a series of super novae (e.g., Gounelle et al., 2009), or injection of super nova ejecta directly into the solar nebula after it had formed (Ouellette et al., 2007). Given that live ^{26}Al was homogeneously distributed in the early Solar System (as inferred by the agreement in ^{26}Al ages and Pb–Pb ages e.g., Amelin et al., 2002), including in CV CAIs, this material must have been present and well mixed in a time less than 10^4–10^5 years after the solar nebula formed. If ^{26}Al was introduced to the nebula after this time, only a small fraction of refractory grains would contain this short-lived nuclide. Thus the injection of ^{26}Al must have occurred no later than 10^5 years after the disk formed. This is a natural consequence of the models in which short-lived nuclides are injected into the molecular cloud from which the Solar System formed, but not necessarily the case for injection into the disk. While homogenization timescales for materials injected into a disk may be short (Boss, 2008), the time window in which such materials could be injected into the disk is very narrow in this model. While some of the so-called FUN (Fractionation and Unidentified Nuclear isotope anomalies) CAIs appear to have formed in the absence of live ^{26}Al (MacPherson, 2005), they make up a small fraction of the CAI population, and are by no means the majority. Such FUN CAIs may be indicating that ^{26}Al was introduced and homogenized on timescales of $\sim 10^3$ years or less.

Moreover, the ages of refractory objects, more specifically the CAIs, define the age of the Solar System, and $t = 0$ in terms of the sequence of events that are recorded by meteorites and planetary samples. An outstanding question has been how does this $t = 0$ match up with the different stages of molecular cloud collapse, star formation, and disk evolution observed by astronomers? As the refractory grains from the first 10^4–10^5 years of disk evolution here dominate the population in a protoplanetary disk, this suggests that the $t = 0$ in meteoritics must not coincide with any later point than the $t = 0$ assumed here. That is, $t = 0$ as defined by CAIs must coincide with no time later than the instant when the solar nebula largely completed forming from the collapse of the parent molecular cloud. The timescale for molecular cloud collapse and accretion onto the disk are sensitive functions of cloud properties (e.g., Gong and Ostriker, 2009), but are estimated to be on the order of a few times 10^5 years (e.g., Feigelson and Montmerle, 1999; Lee et al., 2008). This suggests that the $t = 0$ in meteoritics coincides with at most a few hundred thousand years after the initiation of collapse of the molecular cloud from which our Solar System formed. This agrees with the conclusions reached by Wood (2004), however, for different reasons – it is not the duration of the particular evolutionary stage of the solar nebula, but rather the subsequent dynamical evolution of the disk and solids that sets what is measured for a formation duration.

While the results discussed here apply to a wide range of plausible disk conditions, further exploration of parameter space can be done and the model improved in a number of ways. For example, only the dynamical evolution of the refractory objects are considered. Dynamical evolution of the ferromagnesium silicates certainly led to variations in their abundances at different locations in the disk – indeed this is critical to allowing planetesimals to form – which would impact the relative amounts of refractory grains and silicates that would be present when a planetesimal formed. Further, coagulation and fragmentation of particles due to collisions with dust grains have been ignored as well – such processes would have affected the overall dynamics of an individual particle, and how it was redistributed within the disk by changing its aerodynamic properties. Also, the model used here was one-dimensional, in that it assumed that all particles at a given location from the star evolved in a similar manner, regardless of their height above the disk midplane. The transport rates of particles in a viscous disk would likely have varied with height above the disk midplane due to the variations in gas density such that outward transport of dust particles would have been significantly more efficient at the disk midplane than when considered in a vertically averaged sense (Ciesla, 2007a, 2009). Such considerations are likely most important at later stages of disk evolution when vertical settling of dust particles is significant. Indeed, preliminary work suggested that the survival of larger CAIs is easier when the two-dimensional variations in radial transport are considered (Ciesla, 2007b). Future work should investigate the variations in radial transport rates with height in a viscously evolving disk, without assuming a steady-state. Based on previous models of Ciesla (2007a, 2009), it is expected that outward transport would be more efficient, and possibly help preserve larger refractory grains for the necessary length of time in the disk. Finally, this work has ignored the possible sequestration of some solids into planetesimals, which may be an ongoing process throughout the time of nebular evolution. This process would constantly remove solids from the nebular gas, preventing them from accreting with materials at later times. As such, the relative abundances of the different materials that would be available to be accreted into a planetesimal would change with time, and thus is important to understand when estimating the compositions of planetesimals that form at different times and locations. By accounting for these various effects, we will be able to better understand the factors that controlled the compositions of planetesimals that formed within our solar nebula.

Despite the possibility of model improvements, the work here does lead to important predictions that can be tested against the meteorite record. First and foremost, this model predicts that while the majority of refractory objects that are preserved in primitive bodies throughout the Solar System would have formed during the first $\sim 10^5$ years after the disk was fully formed, a small fraction of these objects would have formed at significantly later times. If the ages of a large number of refractory objects could be determined, then a large range of ages should be observed, with a sharp decline in probability at younger ages. Further, this distribution should be seen for all refractory objects in all primitive bodies, throughout the Solar System. Thus, if ages of the high-temperature materials collected by the STARDUST mission can be derived, they should correspond to the same time period at which CV CAIs formed. If such data can be collected, in a statistically significant way, it may provide important insights into the rates of mass and angular momentum transport in the solar nebula, throughout its history, and not just during the first $\sim 10^4$ years.

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