The Meteoritical Society

Meteoritics & Planetary Science 44, Nr 10, 1663–1673 (2009)
Abstract available online at http://meteoritics.org

Dynamics of high-temperature materials delivered by jets to the outer solar nebula

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(Received 13 February 2009; revision accepted 05 August 2009)

Abstract–The presence of high-temperature materials in the Stardust collection that are isotopically similar to those seen in chondritic meteorites argues for the outward transport of materials from the hot, inner region of the solar nebula to the region where comets formed. A number of mechanisms have been proposed to be responsible for this transport, with a number of models being developed to show that such outward transport is possible. However, these models have not examined in detail how these grains are transported after they have been delivered to the comet formation region or how they may be distributed in the cometary nuclei that form. Here, the dynamical evolution of crystalline silicates injected onto the surface of the solar nebula as proposed by jet models for radial transport is considered. It is generally found that crystalline grains should be heterogeneously distributed within the population of comets and within individual cometary nuclei. In order to achieve a homogeneous distribution of such grains, turbulence must be effective at mixing the crystalline silicates with native, amorphous grains on fine scales. However, this turbulent mixing would serve to dilute the crystalline silicates as it would redistribute them over large radial distances. These results suggest that it is difficult to infer the bulk properties of Wild 2 from the Stardust samples, and that the abundance of crystalline grains in these samples cannot alone be used to rule out or in favor of any of the different radial transport models that have been proposed.

INTRODUCTION

Despite originating in the coldest regions of the solar nebula, a significant amount of the materials collected by the Stardust spacecraft from comet Wild 2 are minerals that formed at high temperatures, including forsterite and enstatite grains, grains similar to the calcium, aluminum-rich inclusions (CAIs) found in chondritic meteorites, and chondrule fragments (Brownlee et al. 2006; Zolensky et al. 2006; McKeegan et al. 2006; Nakamura et al. 2008; Simon et al. 2008). Such minerals require temperatures in excess of 1000 K to form (Hallenbach et al. 2000), suggesting that either materials in the outer disk were exposed to transient heating events, possibly similar to those responsible for the formation of chondrules in the inner solar system (see recent review by Connolly et al. 2006), or that dust grains were transported from the inner regions of the solar nebula where high temperatures are expected, to the cold outer regions where comets formed. The similar isotopic composition of the Stardust minerals and terrestrial materials points to outward transport as being the source of these materials (McKeegan et al. 2006; Nakamura et al. 2008; Messenger et al. 2008).

A number of mechanisms had been proposed as ways that solids could be transported outward in the solar nebula prior to being accreted into planetesimals. Many of these were actually proposed based on the astronomical detection of crystalline silicates in comets prior to the Stardust mission (see review by Wooden et al. 2007). These models generally fall into two broad categories: jet models in which solids are launched above the disk by winds only to decouple from the gaseous flow and rain back down onto the nebula at a different radial locations (Shu et al. 1996, 1997; Liffman 2005, 2007), and dynamic disk models where various processes operating within the nebular gas allowed solids to migrate outwards through the solar nebula (e.g. Gail 2001; Bockelee-Morvan et al. 2002; Keller and Gail 2004; Ciesla 2007; Mousis et al. 2007; Boss 2008). A new model for outward transport was also recently proposed, suggesting that radiation pressure from the disk and the young Sun may have combined to push grains outward along the surface of the disk where they would then fall back into the disk at large radial distances (Vinkovic 2009). For the purposes of this paper, the grains would be delivered in a similar manner as predicted for the jet models.

To date, transport models have focused on demonstrating that it is possible for materials that originate in one location to migrate to another location. Identifying which of the proposed mechanisms was primarily responsible for delivering materials from the inner solar nebula to the comet formation requires a critical analysis of the timing of the transport, the evolution of those materials after transport, and how the transported materials would have gotten incorporated into the comets and asteroids that we see today. Only by doing so can we move beyond thinking about transport in idealized ways and instead identify distinctive signatures or consequences of the transport mechanisms that may be preserved in comets today.

In this paper, we consider the dynamical evolution of dust particles delivered to the outer solar nebula as proposed by the jet models. The specific goal here is to understand how transport in this manner would allow high-temperature materials to get incorporated into comets. Transport via dynamic disk models will be considered in a future paper. This is by no means a comprehensive investigation, however, it does identify the important issues associated with this mode of transport and sets the framework in which such models should be considered. In the next section, the basic ideas of the jet models for outward transport are reviewed. In the following sections, the dynamical evolution of high-temperature materials as they are injected into a passive solar nebula and one that is evolving viscously is considered. The main points are then summarized and future research directions are discussed.

TRANSPORT ABOVE THE DISK

Jet models for outward transport are in part motivated by the observations of bipolar jets around young stars (see recent review by Bally et al. 2007). These jets are thought to be winds that originate in the inner disk and carry gas approximately perpendicular to the plane of the protoplanetary disk. The particular driving mechanism for these winds remains the subject of debate, though is likely tied to the interactions of magnetic fields with the disk material (Shang et al. 2007; Pudritz et al. 2007). In terms of solid transport, it has been proposed that as the gas is launched in these winds, it would be capable of entraining solids that would also be present (Safier 1993; Shu et al. 1996, 1997; Liffman 2005).

The jet model that is most often invoked in discussing the outward transport of solids in the solar nebula is the X-wind model of Shu et al. (1996, 1997). It was argued that the properties of chondritic materials, such as chondrules and CAIs, could be explained in the context of solids being heated to various degrees close to the young Sun and then launched in ballistic trajectories above the disk as a result of winds driven through the interaction of the magnetic field of the Sun with the inner edge of the solar nebula. The distance to which solids would be launched depended on the intensity of the winds and the aerodynamic properties of the solids. Thus one consequence of this model would be that solids would be sorted by size during transport as large solids would not get pushed outwards as much as small particles and similarly sized particles would land at approximately the same distance from the young sun as one another (Liffman 2005). Further, a specific prediction of the X-wind model was that small CAIs would be present in comets, which has proven to be the case with the discovery of Inti and other CAI-like particles in the Stardust samples (Brownlee et al. 2006; Zolensky et al. 2006; McKeegan et al. 2006; Simon et al. 2008).

While jet models are able to qualitatively explain the presence of high-temperature minerals in comets, it is unclear whether enough solid material would be heated and launched in the jets in order to explain the high abundance of such materials in these icy bodies. Further, these models assume that once solids rained back down onto the nebula, they were incorporated into planetesimals that formed at those particular locations, thus preserving the size sorting that occurred above the disk (e.g., Liffman 2005). Indeed, Stadermann and Floss (2008) proposed that this sorting explained why presolar grains appeared to be so under-abundant in comet Wild 2—that a large amount of small, processed dust grains were launched in a jet and fell back onto the comet formation region, thus diluting the abundance of native materials that escaped processing at high temperatures. If Wild 2 is representative of all comets and it holds up that pre-solar grains are more abundant in primitive meteorites than comets, it has been argued that the same amount of dilution did not occur in the asteroid belt region of the solar nebula. (It should be noted that capture effects, such as the destruction or camouflage of pre-solar grains as a result of the high velocity capture of the cometary particles have also been proposed as being responsible for the observed low abundance of presolar grains in Wild 2 (Messenger et al. 2009; Stadermann et al. 2009).) Whether such dilution of native materials would occur requires following the dynamical evolution of the injected materials once they enter the solar nebula.

INJECTION INTO A PASSIVE SOLAR NEBULA

Once solids re-enter the nebula, in the absence of any other dynamical effects, they will settle to the midplane under the influence of solar gravity. The velocity at which the particles settle is determined by balancing the force of gravity pulling them toward the midplane with the drag force caused as the particles move through the gas, and can be written as (i.e., Cuzzi and Weidenschilling 2006):

$$V_z = -t_s \Omega^2 z \tag{1}$$

where t_s is the stopping time of the particle ($t_s = a\rho/\rho_g c$, with a being the particle radius, ρ the particle density, ρ_g the local gas density, and c the local speed of sound), $\Omega = (GM_\odot/r^3)^{1/2}$

is the local Keplerian frequency, and z is the height above the disk midplane. Here it is explicitly assumed that $z<<r$. The time it takes for a particle to settle to the midplane can then be approximated by t_{settle}~$-z/V_z$~$1/t_s\ \Omega^2$. The settling times for particles of different sizes are shown in Fig. 1. These calculations assume the same disk properties of Weidenschilling (1997) at 30 AU from the Sun, with a temperature of 50 K and a surface density of gas of 29 g/cm^2. The settling times presented assume the particles begin at $z = H$, or one scale-height above the disk midplane (approximately 2.7 AU). For now, we ignore the possibility of coagulation, where dust grains would collide with one another and stick, forming larger aggregates that may settle at more rapid rates. This issue is discussed in grater detail below. (Note that these settling time scales are only rough approximations as the settling velocity varies with height, with settling velocities diminishing at lower altitudes due to the lower vertical gravitational force and higher gas densities which would impeded movement. For the purposes of this discussion, however, these first order time scales are sufficient, with the important point to keep in mind being that these are likely underestimates of the actual settling times).

As can be seen in Fig. 1, the settling time scale decreases with increasing particle size, as the larger bodies have longer stopping times, meaning they move through the gas more readily than smaller ones. The high-temperature materials collected by Stardust largely fell into the range of a few tenths to a few microns in size. If such particles were introduced to this region of the nebula via the jet model, they would take at least 10^5–10^6 years to settle to the midplane where they would then be incorporated into comets.

During the time it would take for these processed particles to settle to the midplane, the solids that would be native to this region of the disk would have begun to coagulate into larger objects. Weidenschilling (1997) examined this in detail, calculating how solids would grow through collisions induced from relative velocities that arise due to Brownian motion, gas drag, and vertical settling. After less than 10^5 years, most of the mass of solids at 30 AU was contained within 10 to 100 m "cometesimals."

All grains that were present in the outer disk would be available to be incorporated into these cometesimals. In fact, dust grains at higher altitudes may serve as the "seeds" for these bodies as after the first ~10^4 years, when Brownian motion serves as the primary source of relative velocities between the solids, vertical settling starts to become the main source of relative velocities between bodies, leading to more rapid aggregation of the solids. Thus a dust grain injected into the upper layers of a disk may be incorporated into these cometesimals provided that it is there very early, before solids grow large enough to settle and deplete the upper layers in solid mass (and thus removing the other grains with which the injected grain could coagulate and settle). Thus cometary grains could only be intimately mixed with native materials and make up a significant fraction of cometary bodies in these models if they were delivered to the outer disk on time scales of <~10^4 years.

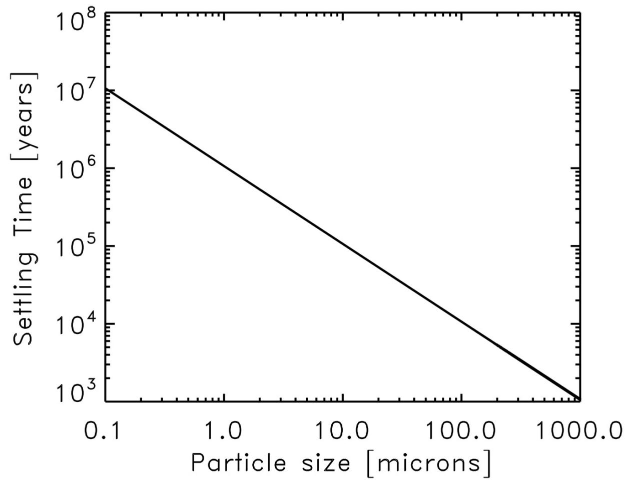

Fig. 1. The time scale for particles of different sizes to settle to the midplane at 30 AU in a passive solar nebula. Coherent mineral grains collected by the Stardust spacecraft are typically on the order of 1 µm in size, though larger, weakly connected aggregates may have been collected and dispersed upon collection.

If a significant fraction of dust grains were delivered on longer time scales, the native materials in the disk would be able to aggregate together, forming bodies that were largely devoid of high-temperature silicate grains from the inner solar nebula. For delivery time scales long compared to the settling time scale of these grains (10^5–10^6 years), comets would likely be built of the cometesimals which formed early from the native materials, with an outer layer of high-temperature grains that slowly settled to the midplane and were swept up by the already formed cometesimals.

If the delivery time scale fell somewhere in between the time scale for the upper layers to be depleted in dust grains via coagulation (10^4 years) and the settling time scale of the injected grains (10^5–10^6 years), then the processed grains would likely have coagulated together before settling to the disk midplane, forming large aggregates that themselves grew to become cometesimals. These cometesimals could have further accreted with one another or with the cometesimals dominated by native grains, to form the comets. This would create cometary nuclei that were heterogeneous in terms of the abundance of inner solar system materials.

Thus in the case of a passive formation environment, the compositional structure of a comet would depend on the time scale of delivery for the processed grains to the outer solar nebula via the jets. Delivery of dust grains prior to the earliest stages of coagulation and growth (<10^4 years) would allow high-temperature grains to be intimately mixed with the native materials. Longer delivery time scales would likely lead to heterogeneous cometesimals or comets as growth would have begun in an environment where high-temperature grains were absent.At present, it is not known to what level the high-temperature materials in comets are mixed with the materials that escaped processing altogether. Indeed, if the material ejected from a comet preferentially comes from the surfaces of the cometesimals that aggregated together to form the comet nucleus, the latter scenarios presented above, where jets deliver dust grains to the outer nebula on time scales of $>10^4$ years may explain why high-temperature materials seem so prevalent, and why unprocessed materials appear to be absent or underabundant: Stardust preferentially sampled a region of the comet dominated by processed grains. If, instead, high-temperature materials are intimately mixed in comets with the native materials from the outer solar nebula, the either these grains were injected very early or it is necessary to accelerate the delivery of processed materials from the upper layers of the solar nebula to the midplane, and to mix the delivered materials with the native materials prior to the formation of cometary bodies.

INJECTION INTO A VISCOUSLY EVOLVING AND TURBULENT SOLAR NEBULA

Rapid delivery of injected grains to the midplane could be achieved if dynamical processes other than gravitational settling operated to transport solids vertically in the disk. Turbulent diffusion is one possibility, given that turbulence has been proposed as the source of the viscosity that drives mass transport in protoplanetary disks such as the solar nebula (e.g., Lynden-Bell and Pringle 1974; Ruden and Pollock 1991; Richard and Zahn 1999). In fact, the magnetorotational instability (MRI; Balbus and Hawley 1991), which is one of the leading candidates for driving mass and angular momentum transport in disks and for generating turbulence, is likely to have been active beyond 10–20 AU for most, if not all, of the lifetime of the solar nebula (Gammie 1996; Glassgold et al. 1997; Sano et al 2000).

Assuming a standard α-viscosity disk where the viscosity (and to first order, the diffusivity) is given by:

$$\nu = \alpha c H \tag{2}$$

where $H = c/\Omega$ is the local scale height and α a parameter that generally falls in the range of $\sim10^{-3}$-10^{-2}, the time scale for particles to diffuse to the midplane from a height of $z = H$ is:

$$t = H^2/\nu = (\alpha\Omega)^{-1} \tag{3}$$

At distances of 20–30 AU from the Sun, this diffusive time scale would be approximately 1000 to 20,000 years. Thus solids would be able to be delivered to the midplane on much shorter time scales than in passive disks, and thus available to be intimately mixed with native solids as they grow to form cometesimals.

Alternatively, if cometesimal formation is delayed compared to the results of the Weidenschilling (1997) models, it would provide more opportunity for processed solids to become intermixed with native materials at a finer level. Again, this could be achieved in a turbulent environment, where turbulence acts to provide an extra source of relative velocities between solids. This extra relative velocity leads to more frequent and more energetic collisions. As solids grow to beyond a certain size, ranging from millimeters to tens of centimeters depending on the conditions in the nebula, these collisions become largely disruptive rather than accretionary. Thus, growth beyond that level is frustrated (for example, see discussion in Cuzzi and Weidenschilling 2006). Growth to cometesimals could then occur through other means, such as the spatial concentration of solids into more and more massive clumps aided in part by the turbulence in the disk (Johansen et al. 2007; Cuzzi et al. 2008).

Thus having high-temperatures solids intimately mixed with unprocessed materials in comets could be a sign that comet formation began in a dynamic, turbulent environment. While turbulence may accelerate the delivery of high temperature materials to the midplane of the solar nebula, the diffusion and corresponding evolution of the disk will serve to redistribute these materials radially prior to their incorporation into comets. In particular, recent work by Ciesla (2009) demonstrated that small grains that are injected onto the surface of a protoplanetary disk are driven inward toward the star due to the rapid flows that develop in a viscous protoplanetary disk (Urpin 1984; Takeuchi and Lin 2002; Keller and Gail 2004; Tscharnuter and Gail 2007). Diffusion also works to dilute the concentration of the injected materials, as it mixes them with the unprocessed solids native to the outer disk. Thus, it is possible that only a fraction of the injected grains would be able to be incorporated into comets, and that their abundance may be significantly diminished relative to the unprocessed grains that would be present there.

To investigate this, the model of Ciesla (2009) was used to examine the dynamical evolution of dust particles injected onto the surface of the outer solar nebula. The disk was assumed to be in steady-state with a constant mass accretion rate throughout the disk of $dM/dt = 10^{-8}$ $M_\odot$/yr, and a value of $\alpha = 10^{-3}$. The structure of the nebula, and the corresponding radial and vertical velocities of the gas and solids, were found as described in Ciesla (2009). The structure of the outer disk was described by the power laws:

$$\Sigma(r) = 65\ (r/20\ \mathrm{AU})^{-1}\ \mathrm{g/cm^2} \tag{4}$$

$$T(r) = 52\ (r/20\ \mathrm{AU})^{-0.5}\ \mathrm{K} \tag{5}$$

In tracking the dynamical evolution of dust grains injected into the disk, the grains were assumed to be injected over some radial range at a height of z = 2.5 H, symmetrically about the midplane. The rate of delivery of these grains was assumed to be constant. To quantify the rate of delivery, we define a delivery time scale, t_d, as the time it would take, in the absence of radial transport, for the mass of injected silicates to equal the mass of native silicates in the region of interest. That is, if we consider a region of the solar nebula between r_1 and r_2, the delivery time scale for these silicates would be:

$$t_d = M_{\mathrm{reg}}/(dM/dt) \tag{6}$$

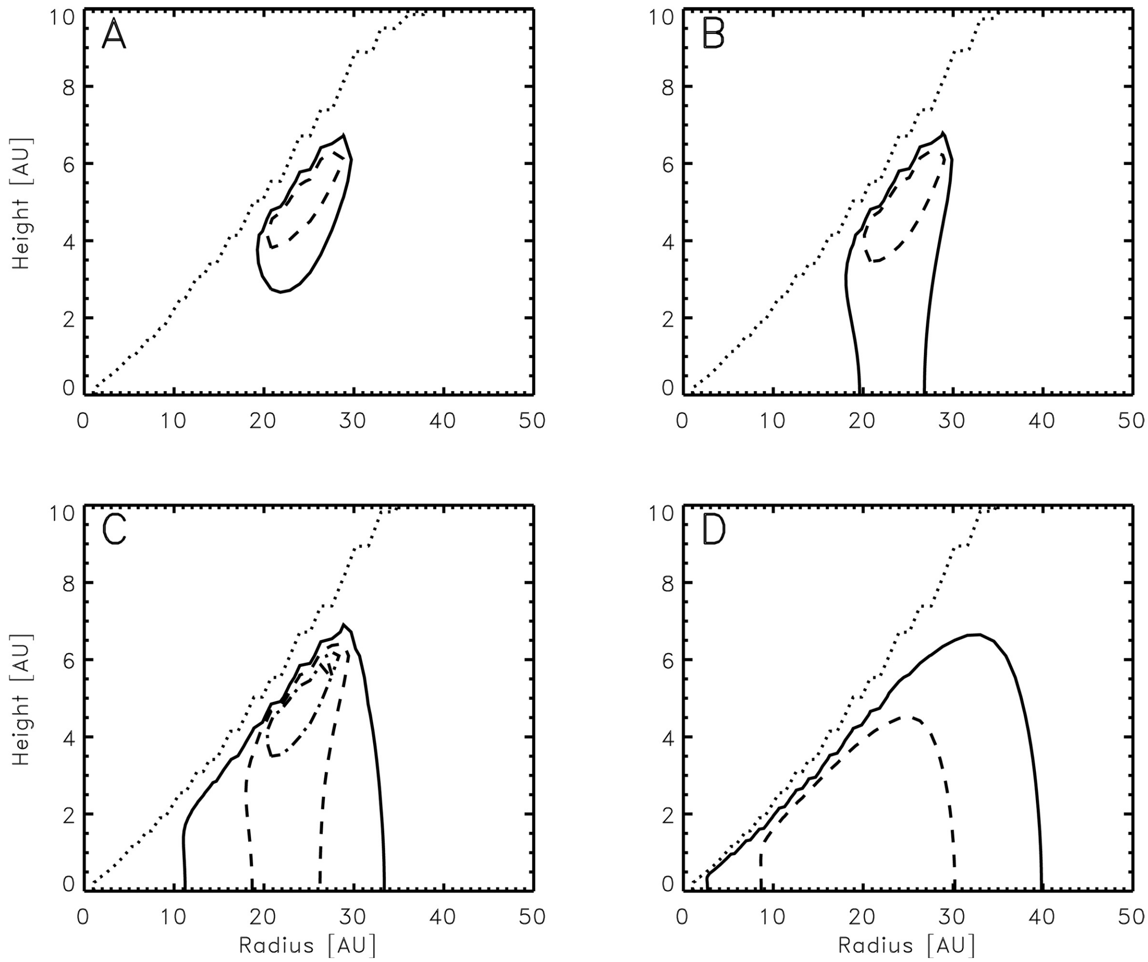

Fig. 2. Contours showing the concentration ($C = \rho_d/\rho_g$) of grains injected from 20 to 30 AU with a delivery time scale of $t_d = 9 \times 10^5$ years. Contours are for $C = 0.001$ (solid line), $C = 0.002$ (dashed line) and $C = 0.003$ (dot-dashed line). Each panel is for different times, 10^5 (A), 2×10^5 (B), 5×10^5 (C) and 10^6 (D) years. The dotted line corresponds to an altitude of $z = 3H$.

where M_{reg} is the mass of disk material between r_1 and r_2. An absolute lower limit to t_d could be found by setting the rate of delivery (*dM/dt*) to the region of interest to the rate at which mass is ejected from the disk (thus assuming all solids ejected in a jet fall back on the disk in between r_1 and r_2). This rate can then be assumed to equal the rate of mass accretion from the disk onto the star, which is an upper limit as discussed by Liffman (2007).

Thus, the rate at which processed materials are introduced to a particular region of the disk is dependent on the mass accretion rate onto the star and the size of the region that they are raining down over. In the disk model considered here, with $dM/dt = 10^{-8}$ $M_\odot$/yr, if materials were injected uniformly into the disk from 0.1 to 100 AU (M_{reg}~0.1 $M_\odot$), this would imply a delivery time scale of ~10^7 years. This is much longer than the lifetime of typical protoplanetary disks (Haisch et al. 2001). Thus, if jets were primarily responsible for the delivery of processed materials to the outer solar nebula, the grains would have had to been injected into a smaller radial span to occur on shorter time scales.

Here we consider two such cases, one where grains 10 µm in diameter (about the upper limit of those crystalline grains collected by Stardust) were injected into the nebula from 20 to 50 AU from the Sun and one where grains were injected between 20 to 30 AU. In these cases, the delivery time scales are ~2.7×10^6 and ~9×10^5 years, respectively. These radial locations were chosen to be illustrative of the outer solar nebula where comets such as Wild 2 are expected to have resided after they formed. While comet Wild 2 may have formed elsewhere or incorporated materials from beyond the regions considered here, the model results can be generalized to other regions of the disk.

The materials were assumed to be added at a constant rate through the time t_d, and injected at heights of z = 2.5 H throughout on each side of the disk midplane. This height was chosen for computational purposes, as the model used here only tracks the dynamics of particles up to z ~ 3H, which accounts for over 99% of the disk mass.

Figures 2 and 3 show how the materials injected into the disk are redistributed with time for the 20 to 30 AU and 20 to

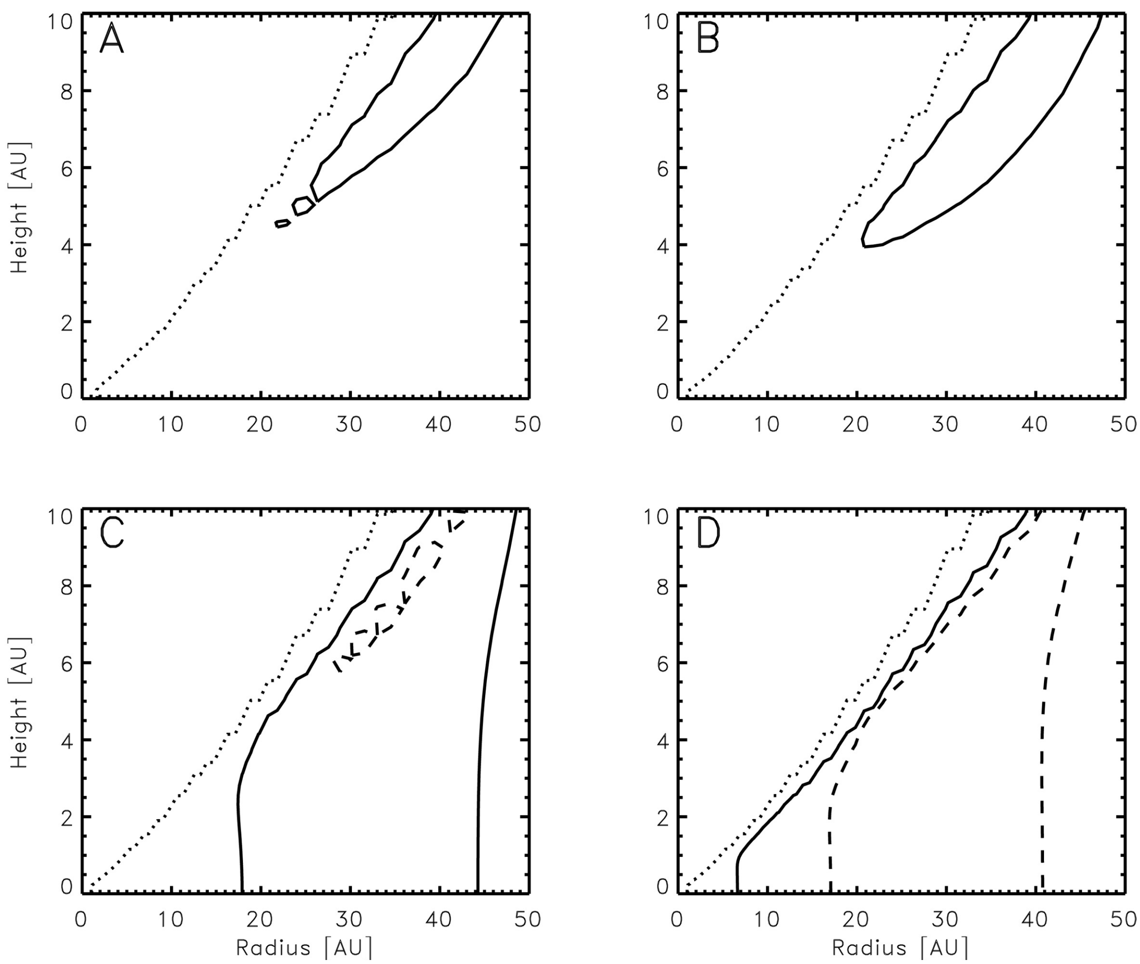

Fig. 3. Same as Fig. 2, but for the case of grains injected from 20 to 50 AU with a delivery time scale of $t_d = 2.7 \times 10^6$ years.

50 AU injection cases respectively. Initially, the concentrations of the grains grow at the points of injection, at the upper altitudes of the disk. These materials are then redistributed by viscous flows, gravitational settling, and diffusion. Because the grains are injected into the upper layers of the disk, the net motions are initially inward as this is the direction of the viscous flows. Vertical settling and diffusion bring grains to lower altitudes, where viscous flows diminish in magnitude and, in fact, change direction around the midplane. This allows the grains to get redistributed throughout the nebula, both inside of and outside of the radial annulus in which they were injected.

Figures 4 and 5 show how the fraction of crystalline grains would change at the disk midplane as a function of time for the two cases considered here. Here it was assumed that all injected materials represented crystalline silicate grains, and that these grains were being mixed with amorphous grains that were native to the outer nebula. The concentration (solid-to-gas mass ratio) of crystalline and amorphous grains are denoted by C_c and C_a respectively, with $C_a = 0.005$ assumed to be constant throughout the disk. The fraction of crystalline grains, f_c, was then found by:

$$f_c = \frac{C_c}{C_a + C_c} \tag{7}$$

In the absence of radial transport, the crystalline fraction at the locations where materials are injected would be expected to be 0.5 at $t = t_d$ for the cases considered here. However, as can be seen, this maximum value is not achieved; instead a maximum of $f_c \sim 0.2$ is reached in these regions.

The reason that the crystalline fraction is kept low is that while the vertical diffusion of particles allow dust grains to be delivered from high altitudes to the disk midplane on rapid time scales compared to the case of a passive disk, radial diffusion and viscous flows work to dilute the concentration of these grains by redistributing them over a larger area within the disk. In the amount of time it takes for particles to diffuse to the disk midplane, turbulence will allow them to be redistributed radially over a comparable distance of $\Delta r \sim 2.5H$ (using the same starting conditions as the cases considered here). Assuming $H \sim 0.08r$, which is typical for the outer regions of a disk where heating is dominated by radiation, this means that materials injected at a given location of the disk would be redistributed over an annulus nearly 0.2r wide (4 AU if injected at 20 AU, for example). This assumes that turbulence is isotropic, meaning that the vertical diffusion coefficient is the same as the radial one. However, Johansen et al. (2006) have shown that in MRI-active regions of the disk, radial diffusivity exceeds vertical diffusivity by factors of 3–5. This would mean that the time scale for delivery to the midplane would be longer, allowing the radial range over which materials would have been redistributed to increase. This would result in even lower fractions of crystalline grains.

While only the case of $dM/dt = 10^{-8}\ M_{\odot}/yr$ was considered here, the results can be generalized to greater mass accretion rates. If mass were being transferred ten times more rapidly, then the disk would be nearly ten times more massive under steady-state conditions. Thus the delivery time scale estimates would be approximately the same as estimated above. Further, as discussed by Ciesla (2009), these higher mass accretion rates would lead to more rapid radial transport, in terms of the radial velocities of the flows at each location in the disk and the greater diffusivity that develops due to the higher temperatures. Thus, injected grains would become equally, if not more, diluted under the same assumptions for more rapidly evolving disks.

As in the discussion of the passive disks above, coagulation and growth of dust grains were not considered here. Coagulation of small dust grains may actually occur more rapidly in a turbulent environment, as turbulence increases the relative velocities of dust grains, allowing collisions to be more frequent (e.g. Weidenschilling 1984; Ciesla 2007). This would result in processed grains being incorporated into bodies that achieve greater settling velocities on short time scales, though this settling may be offset by vertical diffusion to some degree. While continued formation of comets via collisions and sticking would be slow, if it happened at all (Teiser and Wurm 2009), solids could be incorporated into cometary-sized bodies via concentration effects associated with turbulence (e.g., Johansen et al. 2007; Cuzzi et al. 2008).

Again, if coagulation and comet formation were to occur very rapidly compared to the delivery time scale, the first cometesimals or comets to form would be dominated by native materials from the outer solar nebula. Dust grains that continue to be delivered would either then form an outer layer on these bodies, be accreted in aggregates dominated by processed materials, or form a separate population of comets with a higher fraction of crystalline grains (similar to the proposition of Nuth et al. 2000). This would make for very heterogeneous distributions of crystalline silicates within the cometary population or individual comets themselves.

If the formation of comets occurs on time scales that are comparable to or longer than the delivery time scales of these grains, then the processed grains can become mixed with the native grains to a finer level. However, as shown here, this can lead to significant dilution of the materials. As centimeter- to meter-sized bodies form, they will redistribute

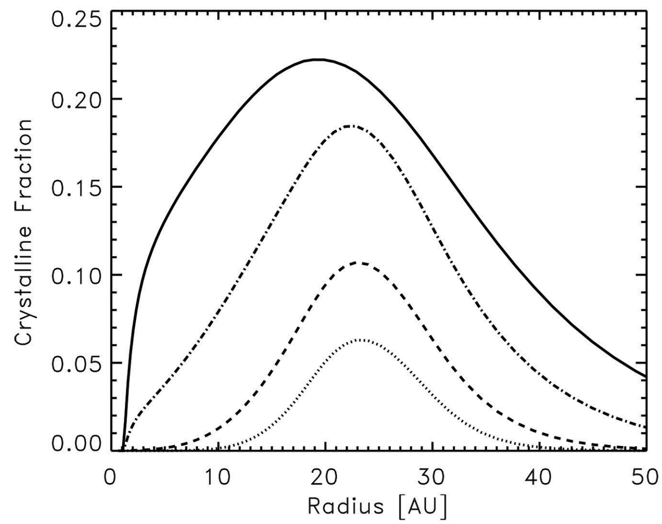

Fig. 4. Plot of the silicate crystallinity fraction, f_c, at the disk midplane at different times for the case of grains injected from 20 to 30 AU with a delivery time scale of $t_d = 9 \times 10^5$ years. The plotted times correspond to the same times plotted in Fig. 2, 10^5 (dotted), 2×10^5 (dashed), 5×10^5 (dot-dashed) and 10^6 (solid) years.

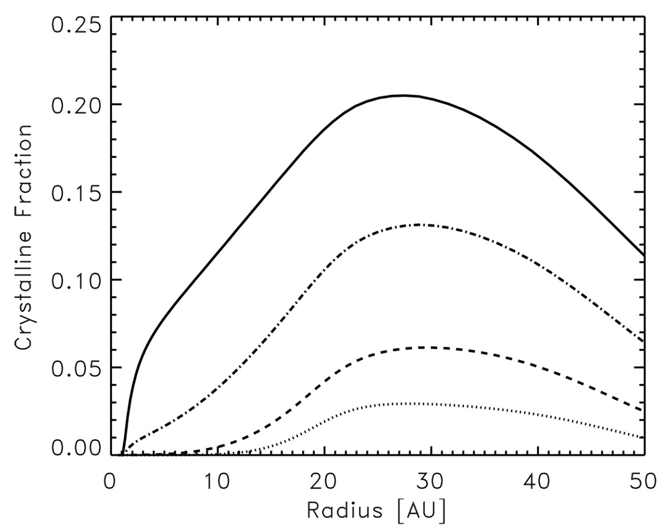

Fig. 5. Same as Fig. 4, but for the case of grains injected from 20 to 50 AU with a delivery time scale of $t_d = 2.7 \times 10^6$ years.

the injected grains by gas drag migration, meaning that the concentration of processed grains may be even lower than that found above.

DISCUSSION

While jets launched from the inner solar nebula may be able to deliver high-temperature materials to the outer solar nebula, the time and abundance at which they will be available to be accreted into comets is highly dependent on their rate of delivery and the dynamic environment into which they are injected. If the delivery of grains to the outer nebula was slow, this likely would lead to a heterogeneous distribution of the grains within a comet or within the cometary population as a whole, whereas rapid delivery would allow for more fine mixing between the injected and native grains. If the disk environment into which they were injected was turbulent, this would lead to dilution of the injected grains, limiting the abundance at which they would be present in the comets. Thus evaluating whether the jet model was primarily responsible for the outward transport of dust grains in the solar nebula, or the conditions under which it operated, requires a detailed understanding of the distribution of the high-temperature materials in different comets and within individual cometary nuclei themselves.

Whether comets have significantly different abundances of crystalline silicates from one another is still an open question. For example, observations of the cloud of material ejected from comet Tempel 1 as a result of the Deep Impact mission suggest the presence of greater amounts of phyllosilicates than has been reported from the Stardust collection (e.g., Lisse et al. 2006). Tempel 1 is also a Jupiter family comet, thought to originate in the same region as Wild 2. If they differ significantly in the abundances of the minerals they contain, this would suggesting, perhaps, that these objects formed at different times, as the properties of the dust present in the outer nebula evolved.

Further, it remains unclear how compositionally homogeneous a given cometary nucleus. As summarized in Bockelee-Morvan et al. (2002), observations of comet Hale-Bopp led to different estimates of the fraction of crystalline silicates in that single comet, with values ranging from 30 to 90%. As discussed by Bockelee-Morvan et al. (2002), these differences may be due difficulties in interpreting the spectra or different assumptions made by the different groups who reduced the data. However, it could also be due to variations in the abundance of crystalline grains in the coma with time—the observations used to make these estimates were made at different times within a period of one year. Thus if the nucleus of Hale-Bopp was heterogeneous in terms of its distribution of processed and unprocessed grains, the different estimates may be due to sampling different regions of the comet or due to crystalline and amorphous silicates not being well mixed.

The Stardust samples currently do not provide any further insight into the fraction of crystalline grains that are present within the cometary population or within comet Wild 2 itself. While estimates have been made recently by Westphal et al. (2009) that 50% of the materials in comet Wild 2 formed in the inner solar nebula, much of the Stardust collection remains to be analyzed. Further, Wild 2 is just a single comet—the diversity of meteorite types and classes alone indicates that a given region of the solar system can give rise to a wide variety of parent bodies.

It must also be remembered that the spacecraft only sampled materials ejected from comet Wild 2 at a single time—given the observations of Hale-Bopp, had the spacecraft rendezvoused with the comet at a different time, the materials that would have been collected may have been very different. Thus it is difficult right now to use cometary data to rule in favor or against a given scenario for the outward transport of high temperature minerals.

Nonetheless, it is interesting to note that the lowest estimate of the crystallinity fraction in comets exceeds the maximum fraction found in the turbulent transport cases considered here. This suggests that, if high-temperature materials were delivered to the outer nebula via jets, either the comet was heterogeneous in terms of the distribution of injected grains and that the Stardust collected materials from a region which had a high abundance of such grains, or that the injected grains could not have been diluted beyond the levels calculated here.

It is also important to consider whether there are effects beyond those considered here that may lead to a different conclusion. One obvious way of reaching larger crystallinity fractions would be by delivering grains to outer regions of the nebula on much shorter time scales than considered here. Specifically, the delivery time scale for dust grains, t_d, would have to be shorter than the time scale for radial redistribution. This latter time scale can be taken as the time scale for vertical diffusion to the disk midplane because during the time period that the grains are moving vertically, they will also diffuse the same distance radially, becoming diluted among the native materials already present. Based on the definition of t_d, this could be achieved if the solar nebula were not in a steady-state configuration as assumed here. If the disk were not in steady-state, then the amount of material in the outer disk could be much lower than estimated here for a given *dM/dt*. If this were the case, there would be less material available to dilute the injected grains, allowing greater crystallinity fractions to be achieved. Such a scenario would be most likely to occur in the earliest stages of disk evolution ($t \sim$ a few times 10^5 years), making the crystalline silicates in comets relatively old, and predating typical chondritic materials (except for CAIs). Variability in accretion rates in young protoplanetary disks has been observed, and such effects have been invoked to explain the dramatic increase in luminosity associated with FU Ori events (e.g. Hartmann and Kenyon 1996) and less energetic (and shorter duration) variability such as seen in V1647 Orionis (Aspin et al. 2009). How this variability relates to the rate at which materials are ejected in a jet requires further study.

Further, if the materials launched in jets were not done so in a quasi-axisymmetric manner as assumed here, but rather in a clumpy way, those grains may be injected in a way that essentially lowers their delivery time on a local scale. Rapid cometesimal formation (~a few orbital periods) would then be needed to ensure that these grains are not diluted by the dynamic processes discussed here as well as the differential rotation of the disk. This would also likely lead to differences in crystallinity fractions among the different comets that form.

The results of this study and the above discussion are not limited to the case of cometary grains, and can be generalized to any materials that are proposed to have processed near the Sun and then transported outwards by a jet. That is, unless accreted very rapidly into planetesimals, any sorting that took place in the jet or memory of where things would have been injected into the disk would be lost over a relatively short period of time due to the dynamical evolution of the grains within the nebula. While not important for the small dust grains considered here, gas drag migration of the solids allows materials to be radially transported large distance from where they are first introduced into the disk, even in passive disks. In the case of evolving disks, the flows and diffusion associated with the gaseous motions would allow materials from different locations in the disk to be mixed together.

CONCLUSIONS

The materials injected into the comet formation region via protostellar jets would be diluted by the transport and mixing processes that are expected to take place in an evolving protoplanetary disk. This would limit the relative abundance of crystalline silicates in comets to levels that appear to be below the estimated abundances based on telescopic observations. If the solar nebula were passive, the amount of time that it would take for crystalline grains to be incorporated into comets would likely exceed the time scale for cometesimal formation. This suggests that comets themselves would be very heterogeneous over large scales in terms of their silicate crystallinity.

A number of transport models have been proposed to explain the presence, and inferred abundances, of high-temperature minerals in comets. Here it was shown that in the case of the jet models for transport that the abundance of crystalline grains in a single comet would be highly dependent on the rate of injection and timing of cometesimal formation. In most cases considered, the fractions of crystalline grains would likely be heterogeneously distributed within a comet or population of comets. This means that inferring the abundances of crystalline grains from a small sample of material from a single comet may give misleading results.

While not explicitly modeled here, a similar analysis can be carried out for disk modes of transport. Ciesla (2009) demonstrated that the outward transport of materials from the hot, inner regions of a viscously evolving protoplanetary disk may occur on time scales of ~10^5 years or longer, depending on the properties of the disk. If comet formation took place on shorter time scales than this, then a heterogeneous distribution of processed materials would be likely in primitive bodies in the outer solar nebula. Boss (2008) argued such transport could occur on shorter time scales, possibly ~10^3 years, leading to a relatively homogeneous distribution of processed grains relative to the native materials. This would make it more likely that cometary nuclei and cometary bodies would have more uniform compositions. More work is needed to investigate the consequence of these modes of transport in detail, however.

Certainly more data from comets would improve our estimates on crystallinity fractions, their variation from comet to comet, as well as the level of homogeneity in a single comet. Such information is necessary if we are to use the abundance of crystalline silicates within comets as a means of evaluating models of outward transport in the solar nebula. Given the small mass of materials that we have to work with, we must consider other ways of evaluating the models of outward transport. For example, we can focus our attention on how grains would be processed in terms of chemical alteration, morphologic changes, or through exposure to different radiation environments as a result of transport and how that compares to the high-temperature materials in the Stardust collection. The environments to which grains would be exposed during transport in jet and disk dynamic models would be very different, with the jet models exposing the grains to the harsh environments near the Sun and near vacuum of space above the disk, while dynamic disk models keep the grains in contact with the nebular gas with which it can react. If differences in alteration can be predicted and identified in the Stardust samples, then we may be able to identify the mechanism primarily responsible for the outward transport of grains in protoplanetary disks.

Acknowledgments–This work was supported by NASA Grant NNX08AY47G (PI: F. Ciesla). The author thanks two anonymous reviewers for their helpful comments and John Bradley for editorial handling of this manuscript. The author also thanks the organizers and participants at the workshop on Timber Cove for stimulating discussions that helped motivate this study.

Editorial Handling—Dr. John Bradley

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