Meteoritics & Planetary Science 44, Nr 10, 1675–1681 (2009)
Abstract available online at http://meteoritics.org

Nebular mixing constrained by the Stardust samples

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(Received 15 January 2009; revision accepted 14 September 2009)

Abstract–Using X-ray microprobe analysis of samples from comet Wild 2 returned by the Stardust mission, we determine that the crystalline Fe-bearing silicate fraction in this Jupiter-family comet is greater than 0.5. Assuming this mixture is a composite of crystalline inner solar system material and amorphous cold molecular cloud material, we deduce that more than half of Wild 2 has been processed in the inner solar system. Several models exist that explain the presence of crystalline materials in comets. We explore some of these models in light of our results.

INTRODUCTION

Comets, if composed of pristine interstellar material, should contain only amorphous silicates since interstellar silicates are almost entirely amorphous (Kemper et al. 2004). However, infrared observations have shown crystalline silicates to be present in comets (Hanner et al. 1994). At temperatures above ~1000 K, amorphous silicates could anneal to crystalline silicates (Hallenbeck et al. 1998), but a heating source strong enough in the protoplanetary disk has proven elusive. Harker and Desch (2002) propose that nebular shocks can anneal silicate dust grains at 10 AU. Comets forming here will be scattered into the Oort cloud and are observed as long-period comets. Gas densities $\geq 10^{-10}$ g cm^{-3} are required to anneal silicate grains with the 5 km s^{-1} shocks modeled by Harker and Desch (2002); the gas density becomes too low beyond 10 AU to anneal silicates. Harker and Desch (2002) state: "Therefore, comets forming in the Kuiper belt region (greater than 35 AU) should not contain crystalline silicate dust annealed by shocks." Similarly, infall of gas from the parent cold molecular cloud (Ruzmaikina and Ip 1994) and cloudlet accretion (Tanaka et al. 1998) can heat material most effectively at higher gas densities in the inner disk. In the outer disk where short-period comets form, shocks generated by phenomena like these will not heat grains to high enough temperatures to anneal crystalline silicates (see Figs. 9 and 10 of Iida et al. [2001]). Alternatively, several different mechanisms to transport inner solar system material to the comet-forming region in the outer disk have been proposed to explain the observational presence of crystalline silicates in comets. With the recent return to Earth of samples from an actual comet, the presence of inner solar system material in a comet can be confirmed in the laboratory, and the explanation of how it got there becomes even more pressing.

NASA's Stardust mission returned samples from Jupiter-family comet Wild 2 to Earth for study. Analysis of these cometary particles in the laboratory led to the almost immediate discovery of refractory minerals that formed in the inner nebula (Simon et al. 2008). In addition to the astronomical observations of crystalline material in comets, the Stardust results made it impossible to ignore the need for a mechanism to transport material from the inner nebula to the outer nebula.

The discovery of individual refractory minerals confirmed the need for nebular mixing, but because the reports were identifications of individual particles, they do not quantitatively address how much inner solar system material is in Wild 2. This is the objective of this study. We report synchrotron-based X-ray microprobe measurements of the relative concentrations of amorphous and crystalline Fe-bearing silicates of 194 fragments in 11 Stardust tracks, and constrain the fraction of inner solar system material in comet Wild 2. We will also discuss the implications our results have on various proposed mechanisms to move inner nebula material to the outer nebula.

MEASUREMENTS

The detailed experimental methods are given in Westphal et al. (2009); we summarize them here. We extracted 11 Stardust

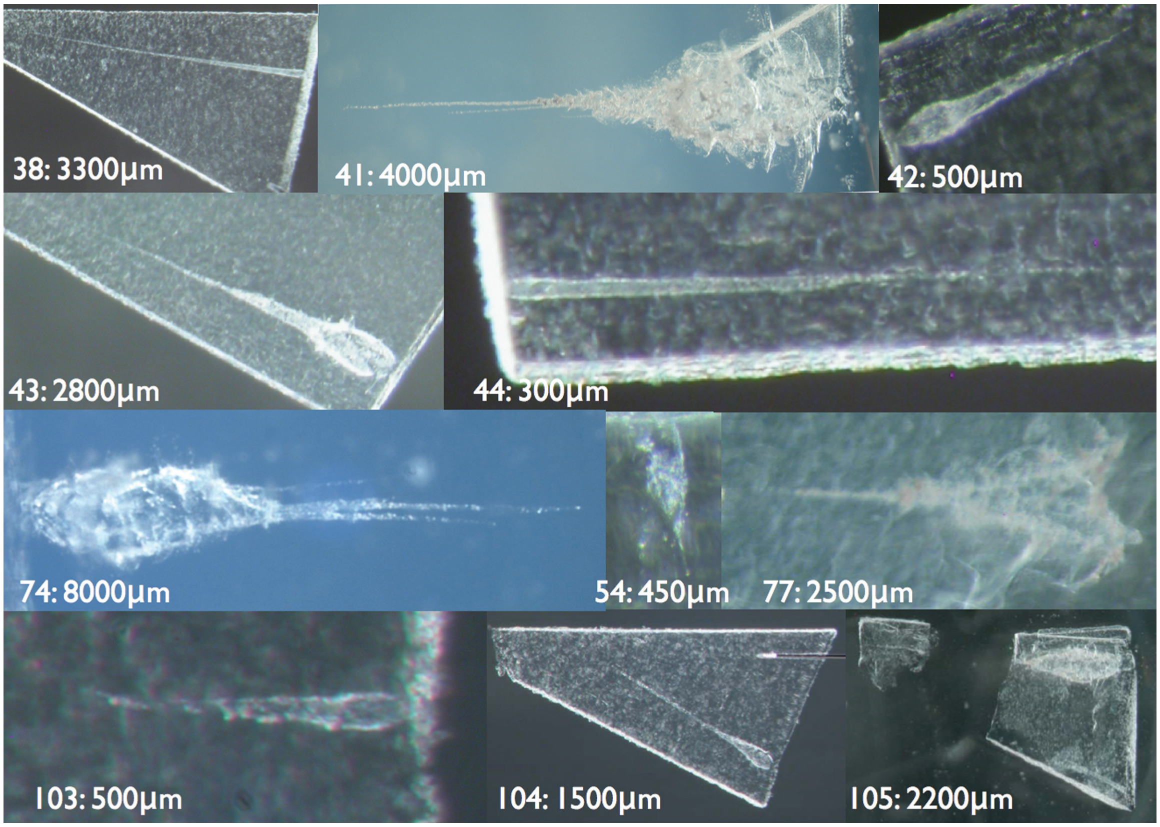

Fig. 1. Optical images and lengths of the 11 Stardust tracks chosen for this study.

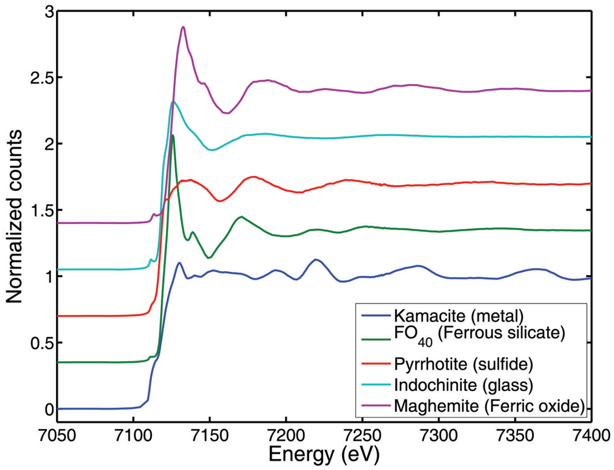

Fig. 2. Representative XANES for metal, ferrous silicate, sulfide, ferric oxide, and glass.

tracks using robotically controlled micromanipulators and pulled-glass microneedles (Westphal et al. 2004). These 11 were chosen randomly from the population of tracks that were at nearly normal incidence to the collector surface. The tracks were of various sizes and shapes (as shown in Fig. 1), ranging from several hundred microns to a few millimeters in length. The 11 tracks we analyzed consisted of a mixture of bulbous and carrot tracks.

We acquired Fe K-edge micro X-ray absorption near-edge structure spectra (µXANES) on 194 fragments (still trapped in aerogel) from the 11 Stardust tracks using beamline 10.3.2 at the Advanced Light Source (Marcus et al. 2004). The Fe-bearing mineral composition of each fragment was determined by fitting the Fe µXANES data to a library of 54 Fe-bearing mineral and glass standards (for details on fitting the cometary XANES spectra to reference standards, see Section 2.3.1 of Westphal et al. (2009)). The glass standards, while degenerate with each other, are easily distinguished in their µXANES data from the crystalline mineral standards. In particular, the Fe XANES of glasses 75–200 eV above the edge is much flatter than crystalline material due to the lack of well-defined second- and higher-neighbor coordination shells around Fe (see Fig. 2).

It is not practically feasible to acquire XANES of all of the particles in the 11 Stardust tracks we examined. After mapping the track in X-ray fluorescence (XRF), we chose the particles with the strongest Fe Kα-emission for XANES analysis. The larger particles ended up in the deeper parts of the Stardust tracks; the area closer to the space-exposed surface (the "bulb") typically contains smaller particles. Therefore, the deeper particles were analyzed more frequently than the bulb particles, which would introduce a bias if the cometary composition varied along the track. To compensate, we computed the integrated Fe Kα fluorescence intensity from the track XRF map and compared this to the XANES edge jumps (also a measure of the amount of Fe in the particle (Stöhr 1992; Kelly et al. 2008)). This allowed us to derive a bulb undersampling correction factor that could be applied to the XANES measurements in the track.

The accuracy of the technique of fitting the Wild 2 XANES to our standards library was tested in a number of ways. For example, we artificially mixed the spectra of standards into cometary XANES, and verified that the fitting procedure accurately reproduced the input mixture in the computed composition. We found errors induced by XANES degeneracy to be approximately 5%. The systematic error due to the XANES fitting procedure is small compared to our statistical uncertainty. Further details of the method and its uncertainties are given in Westphal et al. (2009).

Using this procedure, we determined the crystalline fraction of the Fe-bearing minerals in each of the 194 fragments. By weighting each fragment by the magnitude of the XANES jump, we were able to determine the crystalline fraction of the Fe-bearing minerals of comet Wild 2.

RESULTS

Weighting these tracks by their relative masses yields a bulk Wild 2 crystalline silicate fraction of Fe-bearing minerals. However, hypervelocity capture of cometary grains into aerogel may convert crystalline phases to amorphous phases (see, e.g., Okudaira et al. 2004), though the reverse process is unexpected because of the short time scale for capture. Concerning the latter point, we saw no evidence of crystalline silicates in the tracks of basalt glass projectiles shot into aerogel at speeds close to the Stardust capture velocity (Marcus et al. 2008). Because of this, our derived crystalline fraction is a lower limit.

To determine statistical uncertainties in the crystalline fraction, we used the bootstrap method (Chernick 1999). This is a Monte Carlo based approach that is appropriate when determining the confidence limits on the mean of a distribution when, as here, the dispersion of the data is not known a priori. It is equivalent to asking the question: How different would the result be if we looked at a different set of 11 tracks chosen from our ensemble? From this new ensemble, we recalculated the crystalline fraction η. After computing 10,000 trials, we took the 9772nd entry in a descending sorted list, which is our 2σ lower bound of the Fe-bearing crystalline silicate fraction:

$$\eta > 0.50\ (2\sigma)$$

Even though this survey of particles is a large one relative to other studies of the Stardust Wild 2 samples, the amount of material we analyzed is still, of course, much smaller than is typical in meteorite studies. The uncertainty in our calculation of the Fe-bearing crystalline silicate fraction, with the assumption that the 11 tracks are representative of the collection diversity, reflects the size of our sample: if we were to sample much more of the comet, the uncertainty in the lower bound quoted above would decrease.

Table 1. Crystalline silicate fraction for each of the eleven tracks studied.

Track	Crystalline silicate fraction
38	1.00
41	0.46
42	1.00
43	0.77
44	1.00
54	1.00
74	0.52
77	0.99
103	0.96
104	0.82
105	0.71

One could ask the question: is the Stardust collection a representative sample of the entire comet? We have no reason to believe that the 11 impactors that we studied were related to each other in any way other than having a common origin in Wild 2. We therefore treat these impactors as independent, albeit small, samples of the comet. Indeed, we suggest that this sample may be more representative of the comet than other samples that might be collected in a future sample-return mission, such as large samples of cometary regolith, which would have been exposed to the Sun for many years. In contrast, Stardust probably collected relatively pristine material emitted from jets originating in the interior of the comet. These jets are clearly visible in images taken during the encounter with Wild 2.

The Stardust collection is a sample from one Jupiter-family comet. Unlike the meteorite collection, we are unable, at this point, to analyze samples from multiple comets. If the Jupiter-family comets are all alike, then perhaps the Stardust samples would suffice to explain this class of objects. The question of compositional diversity within Jupiter-family comets (as determined by remote sensing) is open to debate and is complicated by the different dynamical histories of individual comets (Weissman 1999). Until we obtain samples from a number of Jupiter-family comets, we must keep in mind that the Stardust samples are single representatives of a very large collection of objects.

With the Fe-bearing crystalline silicate fraction derived above, and the assumption that the crystalline material had to come from the inner nebula, where temperatures were high enough to anneal amorphous silicate grains, we can deduce the mixing fraction of inner and outer solar nebula material in comet Wild 2. This study is only concerned with Fe-bearing silicates; it would be interesting to measure the crystalline fraction of the finer-grained Mg silicates as their formation in the early nebula was likely different from silicates containing substantial amounts of Fe (Grossman 1972). We assume it is necessary to transport the inner system material outward to a comet formation region in the outer disk because the comet could not have survived or formed in the conditions required to crystallize amorphous grains. We define Ψ to be the molar fraction of Wild 2 that is inner nebula material, so $1-\Psi$ is the molar fraction of cold molecular cloud material, η_{in} is the crystalline fraction of inner nebula material, η_{cmc} is the crystalline fraction of cold molecular cloud material, x_{in} and x_{cmc} are the fraction of Fe atoms residing in silicates (because our Stardust measurements were only sensitive to Fe) in the inner nebula and cold molecular cloud, respectively. We can write the crystalline fraction in comet Wild 2 as:

$$\eta = \frac{(1-\Psi)x_{cmc}\eta_{cmc} + \Psi x_{in}\eta_{in}}{(1-\Psi)x_{cmc} + \Psi x_{in}} \tag{1}$$

Astronomical observations show the interstellar medium to be nearly entirely amorphous (Kemper et al. 2004), so we take η_{cmc} to be zero, and the hot inner nebula will crystallize the Fe silicates, so we set η_{in} to be equal to one. Values of $\eta_{in} < 1$ lead to higher lower limits on Ψ, so this is a conservative assumption. Defining $f = x_{cmc} / x_{in}$, the above equation reduces to:

$$\Psi = \frac{f}{1/\eta - 1 + f} \tag{2}$$

If we assume that the average fraction of Fe atoms in silicates in the inner nebula and the cold molecular cloud are the same, $f = 1$, we can derive a lower bound on the fraction of Wild 2 material from the inner nebula: $\Psi > 0.5$.

DISCUSSION

In the early history of solar system formation, the protoplanetary accretion disc inherited silicate dust from the parent molecular cloud in an amorphous state. Close to the protosun, where the temperature exceeded ~1000 K, the amorphous dust annealed into crystalline grains. The annealing process could have been episodic: recently, the first observations of thermal annealing of amorphous grains into crystalline forsterite were made in the accretion-induced outburst of the young Sun-like star EX-Lupi (Ábrahám et al. 2009). In the absence of radial transport, Wild 2, thought to have formed in the Kuiper Belt between ~20 and ~40 AU, would be composed of dust that was never hot enough to anneal. As calculated by Gail (2001), radial mixing by diffusion moves the inner crystalline material radially outward in the disc so that a significant fraction of grains at several AU are crystalline. However, this radial mixing for reasonable values of the mass accretion rates does not move enough of the inner system crystalline grains to the outer system to explain the crystalline fraction $\eta > 0.5$ that we derived for Wild 2. If the mass accretion rate is extremely large (~10^{-5} solar masses per year or more), the Gail models could reproduce our Wild 2 results.

Other methods to transport inner system material to the outer system have been proposed. One mechanism is solar nebula mixing from gravitational torques due to transient spiral arms in a marginally gravitationally unstable disk (Boss 2008). For this to happen, one must assume that strong spiral arms form in the young nebula and dominate the further evolution. If the protosun and early disk were not marginally gravitationally unstable, this mechanism would not be relevant for the solar system. The models of Boss (2008) do not mix in material from beyond 10 or 20 AU, so it is uncertain how much material from >20 AU gets mixed inward. Also, the simulations in the Boss (2008) models are carried out for of order 1000 years, so it is uncertain where the material from the inner and outer disk ends up after a million years.

Vinković (2009) proposes nebular mixing from the non-radial component of the protosun's radiation pressure. This process is efficient for grains one micron and larger that interact efficiently with near IR light emitted from the hot inner disk; smaller grains do not interact efficiently with near IR and do not move far in the disk. However, the larger grains do not produce a strong IR emission feature (Hanner et al. 1994), and so comets with strong IR features likely contain smaller grains that are not transported to the outer disk by this mixing mechanism. Introducing an additional mechanism to move the smaller particles out to the outer disk where they can be incorporated into some comets, like comet Halley, would increase the complexity of this theory. Additionally, Vinković (2009) considers a central star with a temperature of ~10,000 K, which is much more luminous than the Sun.

A promising mechanism to transport inner disk material to the outer disk is the X-wind model (Shu et al. 1996). The notion that young stars accrete disk material at an equatorial boundary zone was challenged by observations of the angular velocities of T Tauri stars: material feeding these stars at their equators should spin them up faster than the rate at which they were observed to be spinning. Additionally, UV observations showed that the radial accretion velocity was too great for equatorial accretion. Königl (1991) proposed that accretional flow is controlled by the star's magnetic field which couples the star to its disk and thus controls the stars angular velocity. In Shu's X-wind model, the solar dipole field strengthens near the co-rotation radius (the radius where the stellar and disk angular velocities are equal, inside of which material falls directly inward) due to the accreting disk material. In this "X-region", accreting disk gas becomes hot and ionized and follows magnetic field lines; ~2/3 of the material follows closed magnetic field lines taking it into the star at high latitudes, and ~1/3 follows essentially open magnetic field lines far from the star to the outer disk, the "X-wind". This mechanism transports gas to large heliocentric distances because it can be thermally ionized to follow magnetic field lines, but exactly how a particle, which is not constrained to move along field lines, is initially launched into its flight is

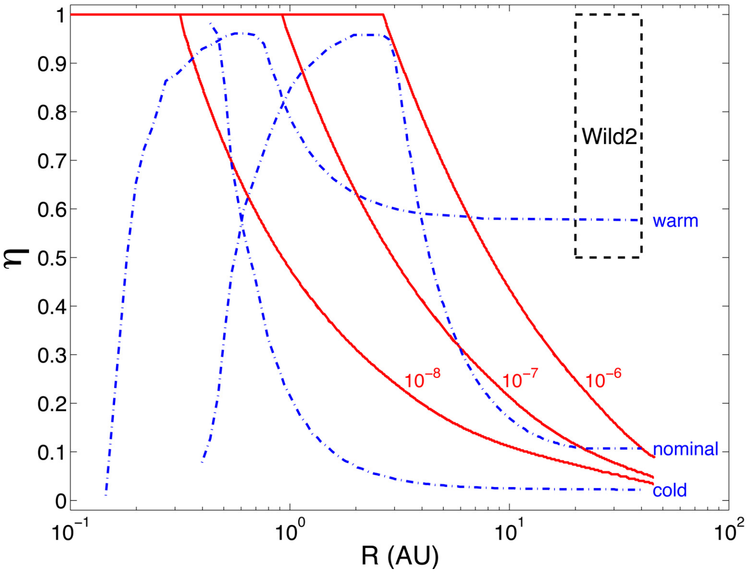

Fig. 3. The crystalline fraction of silicate grains with olivine-like composition as a function of radius for different mass accretion rates (10^{-8}, 10^{-7}, and 10^{-6} solar masses per year) as given by Gail (2001) are shown as solid curves. Gail (2001) also calculates these curves for enstatite; they lie very close to the olivine curves. The Wild 2 result from this work ($\eta > 0.5$) is shown by the dashed black box, assuming Wild 2 formed between 20 and 40 AU. Turbulent radial mixing models as calculated by Bockelée-Morvan et al. (2002) for the cold, nominal, and warm solar nebula one million years after initial crystallization are given by the dot-dashed curves.

not entirely clear. Predictions of how much inner material can be transported to the outer disk at a given distance are uncertain, so it is not currently possible to compare this theory with the results obtained in this study.

Molster et al. (1999) find a significant fraction of Mg-rich crystalline silicates in the disks of red giants in binary systems. The infrared spectrum of carbon-rich giant IRAS09425-6040 shows that it is composed of 75% crystalline silicates. The authors attribute the high degree of crystallinity to processing in the red giant's circumstellar disk, and also conclude that crystallization cannot be caused by heating to high temperatures, but some other process that operates in the disk, as residence time in the disk seems to be necessary for crystallization. The authors state that the possible low-temperature crystallization process removed metals, including Fe, so whatever mechanism is crystallizing these Mg-rich silicates may not be efficiently producing Fe-bearing crystalline silicates and therefore cannot explain the large fraction of these minerals that we see in the samples from comet Wild 2.

Grains crystallized in the hot inner nebula can be diffusively transported to the comet formation zone by turbulence. The amount of material transported to the outer disk is model dependent. The turbulent mixing calculations of Bockelée-Morvan et al. (2002) do not explain our observed Wild 2 crystalline fraction in the nominal solar nebula, but can be consistent with our results in the warm nebula (Fig. 3). The warm and cold nebula models are described by Bockelée-Morvan et al. as "extreme": one of the hottest and one of the coldest models were taken from all the nebulae fitting observational constraints in the work of Hersant et al. (2001). Ciesla (2007) points out that the surface radial density profile (i.e., $\sigma \propto R^p$ where $p < -1.5$) of the protoplanetary disk has a large effect on the ability of turbulence to transport material to the outer disk. A disk with a steep radial profile has less material in the outer disk so there is less mass to drive inward flows resulting from viscous stresses. With a weaker current to fight against, inner disk grains can then more easily diffuse outward. If our solar nebula has a surface density profile of $R^{-1.5}$ (the calculated profile that a collapsed molecular cloud develops initially [Hueso and Guillot 2005]) or steeper, Ciesla's models are consistent with a crystalline silicate fraction greater than 50%, consistent with what we measured in the Wild 2 samples. For shallower density profiles, Ciesla's models do not move enough crystalline material to the outer disk to explain our results. Magnetic field effects and asymmetry of the parent molecular cloud will cause a deviation from a −1.5 surface density profile power law. It is difficult to determine what the surface density power law of the solar nebula was, but Hartmann et al. (1998) argue that the surface density of the disk should vary, not as $R^{-1.5}$, but as R^{-1}. The Ciesla model that agrees with the Stardust results presented here assumes a disk surface density that is slightly steeper than is most likely.

The rate of mixing between the inner and outer nebula may vary significantly over time, but if we assume the solar nebula was a constantly accreting disk, Clark and Pringle (1988) showed that the radial mixing of the disk depends on the ratio (k) of eddy diffusivity to eddy viscosity and not on the actual values of these two parameters. Stevenson (1990) argues that k, which depends on the mechanism of angular momentum transport in the disk as well as the characteristics

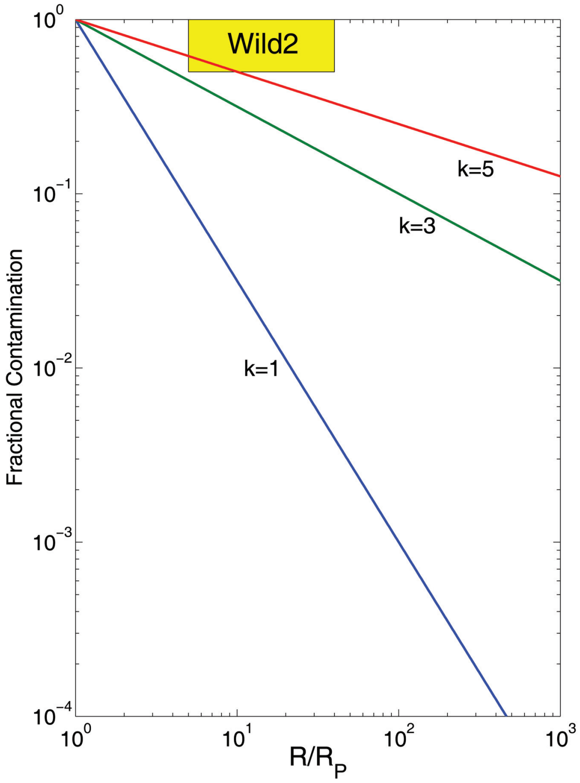

Fig. 4. The fractional contamination of material at heliocentric radius R from material at R_P is shown as a function of R/R_P. Stardust measurements constrain the fraction of inner solar system material in Wild 2 to be >0.5 (region labeled 'Wild 2'). Different values for k, the eddy diffusivity to eddy viscosity ratio, are shown. The Stardust measurements are consistent with k greater than about 3.

of turbulence, is close to unity. This would imply inefficient mixing between the inner nebula and cold molecular cloud material, because the contamination of material at heliocentric radius R from material at radius R_P is calculated by Stevenson to vary as $(R/R_P)^{3/(2k)}$ (see Fig. 4).

Canuto and Battaglia (1988) calculate k to be somewhat higher, between 1.7 to 5.8. Prinn (1990) argues that effects of counter-gradient fluxes in the eddy viscosity (previously neglected nonlinear terms in solar nebula accretion disk models) cause the eddy viscosity to be smaller than the diffusivity. Consequently $k > 1$, and realistically k can approach 10 and still yield a physically realistic picture of the accretion disk. Our results from the Stardust samples support somewhat large values of the ratio of eddy diffusivity to viscosity, around 5, and efficient mixing between the inner nebula and the outer nebula region of cold molecular cloud material. The diffusion mixing models of Bockelee-Morvan et al. (2002) and Ciesla (2007) discussed earlier do not consider values of k greater than 1.

More recently, three-dimensional MHD simulations of the turbulence in accreting disks have resulted in a range of values of k from 0.1 (Carballido et al. 2005) to 1.2 (Johansen and Klahr 2005), though these models can suffer from poor numerical resolution. Pavlyuchenkov and Dullemond (2007), with simplified analytical arguments, derive k = 3. This value, they claim is likely an upper limit on k, and is dependent on their assumptions which include a vertically averaged disk and good mixing between gas and dust. Our results from the Stardust sample are close to the upper bound on k derived by Pavlyuchenkov and Dullemond (Fig. 4). Though these values of k are all of the same magnitude, the ability of inner disk material to diffuse outward is very sensitive to k. A difference of a factor of ~3 will have a large effect on the radial mixing of material in the disk, especially for material that ends up at large heliocentric radius, like the material that formed Wild 2.

CONCLUSIONS

We derive the Fe-bearing crystalline silicate fraction of the Stardust cometary samples to be greater than 0.5 (2σ). With assumptions discussed above, we find that at least half of the Fe-bearing component of comet Wild 2 material is composed of material that was processed in the inner solar system. Various models of nebular mixing have been examined in light of these results, and only if one assumes extreme model parameters (e.g., a very warm nebula, an extremely high nebular mass accretion rate, a steep surface radial density profile, or a large ratio of eddy diffusivity to eddy viscosity) can the large crystalline fraction of the Stardust material be explained. Our results from the Stardust sample point to an early solar nebula more mixed than we've pictured it, or possibly to an unknown mechanism of transporting material from the inner nebula to the outer regions, or to another means of admitting crystalline material into a comet.

Editorial Handling—Dr. John Bradley

REFERENCES

Ábrahám P., Juhász A., Dullemond C. P., Kóspál Á., van Boekel R., Bouwman J., Henning Th., Moór A., Mosoni L., Sicilia-Aguilar A., and Siposet N. 2009. Episodic formation of cometary material in the outburst of a young Sun-like star. *Nature* 459:224–226.

Bockelee-Morvan D., Gautier D., Hersant F., Hure J.-M., and Robert F. 2002. Turbulent radial mixing in the solar nebula as the source of crystalline silicates in comets. *Astronomy & Astrophysics* 384:1107–1118.

Boss A. P. 2008. Mixing in the solar nebula: Implications for isotopic heterogeneity and large-scale transport of refractory grains. *Earth and Planetary Science Letters* 268:102–109.

Canuto V. M. and Battaglia A. 1988. Turbulent diffusivity. *Astronomy & Astrophysics* 193:313–326.

Carballido A., Stone J. M., and Pringle J. E. 2005. Diffusion coefficient of a passive contaminant in a local MHD model of a turbulent accretion disc. *Monthly Notices of the Royal Astronomical Society* 358:1055–1060.

Chernick M. R. 1999. *Bootstrap methods: A practitioner's guide*. Probability and Statistics Series. New York: Wiley. 288 p.

Ciesla F. J. 2007. Outward transport of high-temperature materials around the midplane of the solar nebula. *Science* 318:613–615.

Gail H. P. 2001. Radial mixing in protoplanetary accretion disks. *Astronomy & Astrophysics* 378:192–213.

Clark C. J. and Pringle J. E. 1988. The diffusion of contaminant through an accretion disc. *Monthly Notices of the Royal Astronomical Society* 235:365–373.

Grossman L. 1972. Condensation in the primitive solar nebula. *Geochimica et Cosmochimica Acta* 38:47–64.

Hallenbeck S. L., Nuth J. A., and Daukantas P. L. 1998 *Icarus* 131: 198–209.

Hanner M. S., Lynch D. K., and Russell R. W. 1994. The 8–13 micron spectra of comets and the composition of silicate grains. *The Astrophysical Journal* 425:274–285.

Harker D. E. and Desch S. J. 2002. Annealing of silicate dust by nebular shocks at 10 AU. *The Astrophysical Journal* 565:L109–L112.

Hartmann L., Calvet N., Gullbring E., and D'Allesio P. 1998. Accretion and the evolution of T Tauri disks. *The Astrophysical Journal* 495:385–400.

Hersant F., Gautier D., and Huré J.-M. 2001. A two-dimensional model for the primordial nebula constrained by D/H measurements in the solar system: Implications for the Formation of giant planets. *The Astrophysical Journal* 554: 391–407.

Hueso R., and Guillot T. 2005. Evolution of protoplanetary disks: Constraints from DM Tauri and GM Aurigae. *Astronomy & Astrophysics* 442:703–725.

Iida A., Nakamoto T., Susa H., and Nakagawa Y. 2001. A shock heating model for chondrule formation in a protoplanetary disk. *Icarus* 153:430–450.

Johansen A. and Klahr H. 2005. Dust diffusion in protoplanetary disks by magnetorotational turbulence. *The Astrophysical Journal* 634:1353–1371.

Kelly S., Hesterberg D., and Ravel B. 2008. Analysis of soils and minerals using X-ray absorption spectroscopy. *Methods of soil analysis. Part 5. Mineralogical methods*. Madison: Soil Science Society of America. pp. 387–463.

Kemper F., Vriend W. J., and Tielens A. G. G. M. 2004. The absence of crystalline silicates in the diffuse interstellar medium. *The Astrophysical Journal* 609:826–837.

Königl A. 1991. Disk accretion onto magnetic T Tauri stars. *The Astrophysical Journal* 370:L39–L43.

Marcus M. A., MacDowell A. A., Celestre R., Manceau A., Miller T., Padmore H. A., and Sublett R. E. 2004. Beamline 10.3.2 at ALS: A hard X-ray microprobe for environmental and materials sciences. *Journal of Synchrotron Radiation* 11:239–247.

Marcus M. A., Fakra S., Westphal A. J., Snead C. J., Keller L. P., Kearsley A., and Burchell M. J. 2008. Smelting of Fe-bearing glass during hypervelocity capture in aerogel. *Meteoritics & Planetary Science* 43:87–96.

Molster F. J., Yamamura I., Waters L. B. F. M., Tielens A. G. G. M., de Graauw Th.,de Jong T.,de Koter A., Malfait K., van den Ancker M. E., van Winckel H., Voors R. H. M., and Waelkens C. 1999. Low-temperature crystallization of silicate dust in circumstellar disks. *Nature* 401:563–565.

Okudaira K., Noguchi T., Nakamura T., Sugita S., Sekine Y., and Yano H. 2004. Evaluation of mineralogical alteration of micrometeoroid analog materials captured in aerogel. *Advances in Space Research* 34:2299–2304.

Pavlyuchenkov Ya. and Dullemond C. P. 2007 Dust crystallinity in protoplanetary disks: the effect of diffusion/viscosity ratio. *Astronomy & Astrophysics* 471:833–840.

Prinn R. G. 1990. On neglect of nonlinear momentum terms in solar nebula accretion disk models. *The Astrophysical Journal* 348: 725–729.

Ruzmaikina T. V. and Ip W. H. 1994. Chondrule formation in radiative shock. *Icarus* 112:430–447.

Shu F. H., Shang H., and Lee T. 1996. Toward an astrophysical theory of chondrites. *Science* 271:1545–1552.

Simon S. B., Joswiak D. J., Ishii H. A., Bradley J. P., Chi M., Grossman L., Aléon J., Brownlee D. E., Fallon S., Hutcheon I. D., Matrajt G., and McKeegan K. D. 2008. A refractory inclusion returned by Stardust from comet 81P/Wild 2. *Meteoritics & Planetary Science* 43:1861–1877.

Stevenson D. J. 1990. Chemical heterogeneity and imperfect mixing in the solar nebula. *The Astrophysical Journal* 348: 730–737.

Stöhr J. 1992. *NEXAFS spectroscopy*. New York: Springer. 403 p.

Tanaka K. K., Tanaka H., Nakazawa K., and Nakagawa Y. 1998. Shock heating due to accretion of a clumpy cloud onto a protoplanetary disk. *Icarus* 134:137–154.

Vinković D. 2009. Radiation-pressure mixing of large dust grains in protoplanetary disks. *Nature* 459:227–229.

Weissman P. R. 1999. Diversity of comets: Formation zones and dynamical paths. *Space Science Reviews* 90:301–311.

Westphal A. J., Snead C., Butterworth A., Graham G., Bradley J. P., Bajt S, Grant P. G., Bench G., Brennan S., Pianetta P. 2004. Aerogel keystones: Extraction of complete hypervelocity impact events from aerogel collectors. *Meteoritics & Planetary Science* 39:1375–1386.

Westphal A. J., Gainsforth Z., Ogliore R. C., Butterworth A. L., Fakra S., and Marcus M. A. 2009. Mixing fraction of inner solar system material in comet 81P/Wild 2. *The Astrophysical Journal* 694:18–28.