Astronomical and Meteoritic Evidence for the Nature of Interstellar Dust and its Processing in Protoplanetary Disks

C. M. O'D. Alexander
Carnegie Institution of Washington

A. P. Boss
Carnegie Institution of Washington

L. P. Keller
NASA Johnson Space Center

J. A. Nuth
NASA Goddard Space Flight Center

A. Weinberger
Carnegie Institution of Washington

Here we compare the astronomical and meteoritic evidence for the nature and origin of interstellar dust, and how it is processed in protoplanetary disks. The relative abundances of circumstellar grains in meteorites and interplanetary dust particles (IDPs) are broadly consistent with most astronomical estimates of Galactic dust production, although graphite/amorphous C is highly underabundant. The major carbonaceous component in meteorites and IDPs is an insoluble organic material (IOM) that probably formed in the interstellar medium, but a solar origin cannot be ruled out. GEMS (glass with embedded metal and sulfide) that are isotopically solar within error are the best candidates for interstellar silicates, but it is also possible that they are Solar System condensates. No dust from young stellar objects has been identified in IDPs, but it is difficult to differentiate them from Solar System material or indeed some circumstellar condensates. The crystalline silicates in IDPs are mostly solar condensates, with lesser amounts of annealed GEMS. The IOM abundances in IDPs are roughly consistent with the degree of processing indicated by their crystallinity if the processed material was ISM dust. The IOM contents of meteorites are much lower suggesting that there was a gradient in dust processing in the Solar System. The microstructure of much of the pyroxene in IDPs suggests that it formed at temperatures >1258 K and cooled relatively rapidly (~1000 K/hr). This cooling rate favors shock heating rather than radial transport of material annealed in the hot inner disk as the mechanism for producing crystalline dust in comets and IDPs. Shock heating is also a likely mechanism for producing chondrules in meteorites, but the dust was probably heated at a different time and/or location to chondrules.

1. INTRODUCTION

There are two sources of information on protoplanetary disk evolution: astronomical observations, and for our Solar System, primitive chondritic meteorites, interplanetary dust particles (IDPs) and comets. Astronomical observations are largely confined to the surfaces of disks and have relatively low spatial resolution. Primitive meteorites, IDPs and comets retain a complex record of processes that occurred throughout the early solar protoplanetary disk (solar nebula). This record is still being deciphered. How complete it is and how representative it is of disk evolution in general are open questions.

Silicate dust in the interstellar medium is observed to be largely amorphous (e.g., *Mathis*, 1990; *Kemper et al.*, 2004). One of the most striking observations of protoplanetary disks is that their dust has a significant crystalline component (e.g., *Meeus et al.*, 1998; *Bouwman et al.*, 2001; *van Boekel et al.*, 2004) and it tends to be coarser grained than interstellar dust. Both observations suggest that dust has been thermally processed and has aggregated in these disks even at large radial distances from the central stars. These observations imply either extensive transport of dust from the hot inner regions of the protoplanetary disks (*Nuth et al.*, 2000b; *Gail*, 2004), or perhaps more localized heating mechanisms that operate over large portions of disks (e.g., *Chick and Cassen*, 1997; *Harker and Desch*, 2002).

Comets that formed at large radial distances from the Sun, including Halley (*Swamy et al.*, 1988) and 9P/Tempel 1 (*Harker et al.*, 2005) have a large crystalline component in their silicate dust. Thus, the Solar System appears to have at least one process in common with other protoplanetary disks. Some IDPs may come from comets, and components of chondrites share some features in common with IDPs and comets. This includes presolar material inherited from the protosolar molecular cloud. Thus, it is likely that we can study in the laboratory unprocessed and processed dust that may help constrain the conditions and mechanism of thermal processing.

Here we review astronomical observations of dust in the interstellar medium (ISM), compare them to observations of annealed dust analogs, cometary dust, chondrites and IDPs. Components of meteorites and IDPs retain evidence of several distinct thermal processes that operated in the solar nebula, and we discuss which, if any, may have been responsible for the processing of dust observed in protoplanetary disks. Finally, we discuss the implications and challenges these observations have for the dynamics of protoplanetary disks.

2. CIRCUMSTELLAR, INTERSTELLAR AND PROTOPLANETARY DUST

2.1 Sources of ISM dust - evolved stars and YSOs

The relative importance of ISM dust sources is very uncertain. Most estimates find that red giant (RGB) and asymptotic giant branch (AGB) stars are the main stellar sources of O-rich and C-rich dust (e.g., *Jones*, 2001). *Kemper et al.* (2004) suggest that M supergiants may be as important sources of silicate dust as AGB stars. On the other hand, *Tielens et al.* (2005) estimate that most silicate dust comes in roughly equal quantities from O-rich AGB stars and from young stellar objects (YSO). They also suggest that supernovae could be important sources of dust, but are only able to set upper limits. The crystalline fractions of silicates from O-rich AGB stars and M supergiants are ~10-20% (*Kemper et al.*, 2004). The principle crystalline components are very Mg-rich pyroxene ($Mg_xFe_{1-x}SiO_3$) and olivine ($Mg_{2x}Fe_{2-2x}SiO_4$), with on average 3-4 times as much pyroxene as olivine (*Molster et al.*, 2002). The crystallinity of the young stellar o0bject (YSO) dust is unknown, but it is likely to be dominated by high temperature condensates and annealed material since it is ejected in winds/jets that are generated in the hot inner disk regions.

Carbon-rich AGB stars are the main producers of carbonaceous dust, and they produce about as much dust as O-rich AGB stars. Models of the IR spectra of C-stars suggest that the dust is mostly amorphous C and SiC (*Jura*, 1994).

2.2 Interstellar dust

In the diffuse ISM, grains are subject to modification or destruction in supernova-generated shock waves (*Jones et al.*, 1996). Shattering and vaporization, both associated with grain-grain collisions, and sputtering are the principal modes of modification/destruction. Analysis of gas phase depletions suggests that there is preferential sputtering of the elements, with Si>Mg>Fe (*Tielens*, 1998; *Jones*, 2000), possibly because they are in different phases.

Best estimates of the range of possible diffuse ISM dust compositions indicate that ~59-65 wt% is silicates and ~34-38 wt% carbonaceous (*Zubko et al.*, 2004). The silicate dust appears amorphous and dominated by ≤0.1 μm grains with olivine-like (85%) and pyroxene-like (15%) compositions (Fe/Mg≈1 for both) (*Kemper et al.*, 2004). The crystalline fraction is 0.2±0.2% by mass and if present at all, the crystals are probably mostly forsterite. Given the ~10-20% crystallinity of circumstellar dust being added to the ISM, to maintain such a low crystalline fraction grains must be amorphized on timescales that are ~1-2% of their diffuse ISM lifetime. The amorphization is probably the result of irradiation in supernova-generated shocks (e.g., *Demyk et al.*, 2001; *Brucato et al.*, 2004)

There is considerable uncertainty about the nature and origin of the C-rich dust in the diffuse ISM. *Zubko et al.* (2004) found that between 13% and 100% of the C-rich dust could be in refractory organics, including polyaromatic hydrocarbons (PAHs), the remainder being graphite/amorphous C. Here refractory organics include all non-volatile organic matter that remains in the dust in the diffuse ISM, cometary comas, etc. *Pendleton and Allamandola* (2002) proposed that ~80% of the C in the refractory organic material is in large PAHs (C_{20-200}), originally formed in C-star outflows, that are linked by short, branched aliphatic chains. *Dartois et al.* (2004) suggest that the refractory organics form by UV photolysis of methane ices and contain at most 15% PAHs. Nano-sized carbon grains irradiated with H also reproduce the 3-7 μm IR features ascribed to the refractory organics (*Mennella et al.*, 2002).

The larger gas phase depletions of refractory elements like Mg and Si in diffuse clouds compared to the diffuse ISM (*Savage and Sembach*, 1996) requires condensation of material sputtered and/or vaporized in shocks along with uncondensed material from stellar outflows. The condensed material is probably amorphous and enriched in Si relative to Mg and Fe (*Tielens*, 1998).

In the dense molecular clouds, all but the most volatile elements condense out of the gas. The nature of the silicate dust in molecular clouds is not well understood, but spectra of embedded Class I protostars in the Taurus star forming region show purely amorphous silicate absorption features (*Watson et al.*, 2004) arising from their molecular cloud envelopes and, possibly, their disks. Grains in molecular clouds are protected from the destructive shocks in the diffuse ISM. The amorphous nature of the molecular cloud silicates probably reflects the rapid cycling of material between the dense and diffuse phases of the ISM (*McKee*, 1989; *Draine*, 1990).

2.3 Protoplanetary disks

Observations of classical T Tauri stars in the 10 μm region show much more complex spectra than the ISM, particularly an increased emission at 11.3 μm resulting in a flat-topped appearance (*Przygodda et al.*, 2003; *Forrest et al.*, 2004). Individual T Tauri spectra have been fitted with mixtures of amorphous and crystalline grains (e.g., *Honda et al.*, 2003; *Ciardi et al.*, 2005). However, in general the increased flux at 11.3 μm, the overall spectral shapes and diminished total intensities are consistent with the removal of small grains (~0.1 μm) and only large grains (~2 μm) remaining (*Przygodda et al.*, 2003; *Kessler-Silacci et al.*, 2005). Observations with the Spitzer telescope have unambiguously detected crystalline silicates from T Tauri star disks (*Bouwman et al.*, in preparation). However, at present the data do not exist for correlating crystalline content with age or distance from the star.

The picture is somewhat clearer for disks around the more massive (>2 M_o) Herbig AeBe stars. Crystalline silicates, both forsterite and enstatite, have been unambiguously detected in Herbig AeBe disks (e.g., *Meeus et al.*, 1998; *Bouwman et al.*, 2001; *van Boekel et al.*, 2005) with crystalline mass fractions of up to ~15%. Gradients in the crystallinity of three Herbig AeBe disks have been observed with much higher degrees of crystallinity in the inner 1-2 AU (40-95%) than in the outer 2-20 AU (10-40%) (*van Boekel et al.*, 2004). One of these disks shows a higher forsterite to enstatite ratio in the inner (2.1) compared to the outer disk (0.9). The ages of Herbig AeBe stars are difficult to estimate, but those with crystalline dust, such as HD 142527 (~1 Myr) and HD 100546 (~10 Myr), span the range of pre-main sequence ages.

Little is known about the organic content of protoplanetary disk dust. Gaseous PAH emission has been detected from disks (*Acke and van den Ancker*, 2004; *Habart et al.*, 2004a), but its origin is uncertain. *Li and Lunine* (2003) assume that the gaseous PAHs are released by sublimation of interstellar ices. Alternatively, PAHs might also be generated by pyrolysis of organic matter in dust during the thermal processing that produced the crystalline silicates, or by irradiation/sputtering of organics in the dust.

2.4 Comets

Crystalline silicates, predominantly forsterite, have long been observed in Oort cloud (long period) comets, such as Halley (*Swamy et al.*, 1988) and Hale-Bopp (*Hanner et al.*, 1999). These objects presumably finished their aggregation in the giant planet region (5-10 AU) and were then scattered to large distances by interactions with Jupiter and other the giant planets (*Weidenschilling*, 1997). Kuiper belt objects are thought to have formed and stayed in the outer Solar System at distances of ~35-50 AU from the Sun. Evidence for crystals in Kuiper belt comets has been scarce, but new results for 9P/Tempel 1 show that crystalline forsterite composed roughly half of the silicates (*Harker et al.*, 2005). Thus, there is little evidence for a gradient in crystallinity in the Solar System between the formation regions of Oort cloud and Kuiper belt comets. No mechanism has been proposed for making crystalline material beyond 5-10 AU. The high crystalline content of 9P/Tempel 1 seems to require significant radial transport in the outer solar nebula. It has been argued that some IDPs are cometary in origin (*Joswiak et al.*, 2000), and are most likely to have come from Kuiper belt comets (*Flynn*, 1989). These IDPs potentially provide much more detailed information about the mineralogy of Kuiper belt objects than is possible astronomically (see Section 4.4).

3. CONDENSATION, IRRADIATION AND ANNEALING OF DUST ANALOGS

3.1 Condensation

Models of condensation in stellar outflows and protoplanetary disks usually assume thermodynamic equilibrium and predict crystalline condensates. However, whether equilibrium is maintained will depend on the relative rates of cooling, nucleation and growth. It is evident from observations of AGB outflows that silicate condensates are largely amorphous and, therefore, presumably never achieved equilibrium. Amorphous condensates may also form in the ISM and during thermal events in protoplanetary disks.

In the laboratory, amorphous Mg-Fe-Al-Si-O condensate 'smokes' (nm-sized particulates) have been made in a gas-flow reactor (*Hallenbeck et al.*, 1998; *Nuth et al.*, 2000a) and by laser ablation of target materials (*Fabian et al.*, 2000; *Brucato et al.*, 2002). Not surprisingly, the physical properties of the 'smokes' prepared by the two techniques differ, but in both individual particles from a single experiment exhibit a wide range of compositions even in relatively simple systems (e.g., *Rietmeijer et al.*, 2002). Thus, stellar condensates and condensates from other low pressure and relatively fast cooling environments are likely to be amorphous and compositionally heterogeneous at microscopic scales. Their varied compositions will also influence how they anneal since individual grains will not have ideal mineral compositions, requiring diffusion to or away from growing crystals.

3.2 Irradiation and amorphization

All grains in the ISM, and perhaps some in protoplanetary disks, should have been heavily irradiated. *Demyk et al.* (2001; 2004) estimate that most diffuse ISM silicate grains would be amorphized in a single fast supernova shock. Intense irradiation can produce distinctive microstructures and even chemical changes in grains that can be looked for.

Irradiation of sub-micron-sized grains by ≥400 keV H and He cosmic rays does little to their crystal structure, but leaves identifiable tracks (*Jäger et al.*, 2003; *Brucato et al.*, 2004). Irradiation of olivine and enstatite by He^+ at energies of 0.05, 1, 2.5, 5 and 12.5 keV/amu produces amorphous layers of approximately 4, 40, 90, 200 and 400 nm (*Demyk et al.*, 2001; *Carrez et al.*, 2002a; *Brucato et al.*, 2004; *Demyk et al.*, 2004). These energies are equivalent to shock velocities of roughly 100, 450, 700, 1000 and 1500 km/s. Amorphization by H rather than He to equivalent depths would require even faster shocks, but other abundant more massive ions (e.g., C, N, O) will contribute to amorphization at greater depths. Most of the amorphous grains in the ISM are <100 nm in size (*Mathis*, 1990; *Kemper et al.*, 2004). This would imply that shock speeds of up to ~500 km/s are needed to produce the almost complete amorphization of ISM grains, much higher than is typically assumed (100-200 km/s, *Jones et al.*, 1996). *Slavin et al.* (2004) have shown that grains >0.1 μm can be betatron accelerated to much higher velocities than the shock speed, but they are largely destroyed.

Irradiation can also result in preferential sputtering of elements and changes in composition of the target. However, the experimental results often seem contradictory. Irradiation of olivine (Mg/Mg+Fe=0.9) and enstatite by 4-10 keV He^+ produced preferential sputtering of O and Mg (*Demyk et al.*, 2001; *Carrez et al.*, 2002a; *Joswiak et al.*, 2004). On the other hand, *Dukes et al.* (1999) found no preferential sputtering of Mg or Fe when they irradiated olivine (Mg/Mg+Fe=0.9) with 1 keV H^+ and 4 keV He^+, although preferential sputtering of O reduced the Fe to metal and produced some elemental Si. Reduction of Fe by preferential sputtering of O also occurs in lunar soil grains irradiated at similar energies by the solar wind (*Christoffersen et al.*, 1996). *Bradley* (1994) reported preferential sputtering of Mg and Ca relative to Si, and enrichment of O and Fe, during irradiation of olivine and pyroxene with 20 keV H^+ ions. While *Jäger et al.* (2003) found no preferential sputtering when irradiating enstatite with 50 keV He^+. As a result of preferential sputtering and implantation in interstellar shocks, diffuse ISM grains are unlikely to have ideal (stoichiometric) mineral compositions even if initially they were crystalline, and if they originally contained FeO it is likely to be reduced to metal.

Since amorphization timescales in the ISM are only ~1-2% of the typical grain lifetime, if irradiation is the amorphization mechanism it seems likely that silicates in the ISM will receive ion fluences that exceed amorphization thresholds by factors of up to 50-100. In the experiments, when fluences approach that required for amorphization the samples become vesiculated (*Demyk et al.*, 2001; *Jäger et al.*, 2003; *Joswiak et al.*, 2004). The amorphous rinds on mature lunar soil grains are saturated in solar wind implanted gases, but they are not vesiculated (*Keller and McKay*, 1997). However, in friable lunar breccias the rinds are vesiculated (*Noble et al.*, 2005), as are the solar wind saturated rinds on IDPs heated during atmospheric entry (*Brownlee et al.*, 1998), suggesting that a thermal pulse is needed to produce the vesiculation in these materials. There may be localized heating at the much higher fluxes of the irradiation experiments (*Jäger et al.*, 2003). The fluxes and timescales of interstellar shocks are closer to those of the experiments than solar wind irradiation of lunar grains (100s of yrs). Thus, one might expect interstellar grains to be vesiculated or to become vesiculated on heating.

3.3 Annealing of glasses, smokes and irradiated grains

The mechanisms and kinetics of annealing that might be expected for dust in protoplanetary disks have been explored using glasses, condensate 'smokes' and irradiated grains. Thermal annealing of enstatite glass, produced by quenching of a melt, generated orthoenstatite, except in the lowest temperature experiments conducted at 1000 K when there was incipient formation of forsterite and the SiO_2 polymorph tridymite (*Fabian et al.*, 2000). Annealing of an enstatitic glass during electron irradiation in the transmission electron microscope (TEM) also results in the formation of forsterite and silica (*Carrez et al.*, 2002b). *Rietmeijer et al.* (1986) previously found that for nanoscale grains tridymite and forsterite appears to be more stable than enstatite. $MgSiO_3$-Mg_2SiO_4

‘smokes’ predominantly recrystallize as polycrystalline forsterite and silica (both amorphous and crystalline), along with some MgO in the forsteritic ‘smokes’ (*Hallenbeck et al.*, 1998; *Fabian et al.*, 2000).

Activation energies for annealing rates of ‘smokes’ and glass are similar, although there is some dependence on composition and how the materials were made (*Hallenbeck et al.*, 1998; *Fabian et al.*, 2000; *Brucato et al.*, 2002). Despite the defects produced during amorphization, the activation energy associated with recrystallization of irradiated olivine is similar to that of glasses and ‘smokes’ (*Djouadi et al.*, 2005). Some amorphous silica is produced during the annealing of irradiated olivine.

The experiments suggest that annealed ISM amorphous condensates and irradiated grains are likely to be polycrystalline and even polymineralic. The shapes of annealed grains that were heavily irradiated at low energies may also preserve their original void-rich morphologies. The measured activation energies mean that the annealing times will be a strong function of temperature. For instance, during annealing Mg-Si-O smokes prepared in a gas-flow reactor go through a stall phase. To reach this stall phase requires a few minutes at 1067 K, 23 days at 1000 K, 3900 yrs at 900 K and roughly 10^{14} yrs at 800 K (*Hallenbeck et al.*, 2000). Thus, the presence of crystalline material in disk dust indicates a lower limit on processing temperatures of 800-900 K.

4. EVIDENCE FOR THERMAL PROCESSING OF DUST IN METEORITES AND IDPS

4.1 Meteorites and IDPs

4.1.1 Sources - With a few exceptions, those that come from the Moon and Mars, meteorites are fragments of main-belt asteroids (2-4 AU), with a strong bias towards inner belt asteroidal sources (*Morbidelli et al.*, 2002). While there is an overall gradient of spectral classes in the asteroid belt (*Gradie and Tedesco*, 1982), there has been considerable mixing and it is likely that the meteorite collection has sampled many of them (*Burbine et al.*, 2002).

Some IDPs almost certainly come from comets (*Joswiak et al.*, 2000), but dynamical arguments suggest that most are asteroidal (*Dermott et al.*, 2002). Asteroidal particles would have been part of the Zodiacal cloud, and evolved into Earth crossing orbits through the Poynting-Robertson effect. Thus, they should sample a broader range of parent bodies than do meteorites. Dynamical considerations suggest that cometary IDPs are much more likely to be from Kuiper belt rather than Oort cloud comets (*Flynn*, 1989). Oort cloud comets tend to have higher eccentricities and, therefore, higher Earth encounter velocities (50-70 km/s) than Kuiper belt comets (10-40 km/s). The great majority of particles with velocities >25 km/s are not expected to survive atmospheric entry.

4.1.2 Classification - While there are variations, the bulk compositions of the chondrites are remarkably similar to that of the solar photosphere (excluding H, He, etc.). In terms of bulk composition, the most solar-like of the chondrites are the CIs (*Lodders*, 2003). Because Solar (or CI) is the starting composition from which all Solar System materials evolved, the compositional variations of chondrites and their components are generally expressed as deviations relative to CI.

The compositional variations (fractionations relative to solar) amongst chondrites are largely controlled by the volatility of the elements (Fig. 1). The volatility of an element is normally expressed as its calculated 50% equilibrium condensation temperature from a gas of solar composition at a total pressure of 10^{-4} bars (e.g., *Lodders, 2003*).

Historically, the chondrites have been divided into three groups based on their compositions and mineralogies (ordinary, carbonaceous and enstatite). These in turn have been subdivided (*Scott and Krot*, 2003) into a number of classes: ordinary chondrites into H, L and LL, carbonaceous chondrites into CI, CM, CR, CV, CO and CK, and enstatite chondrites into EH and EL. The classification scheme is still evolving as more meteorites are found - two new groups (R and K chondrites) have been identified, and a number of individual meteorites do not belong to any recognized group.

After formation, the chondrites experienced secondary modification (thermal metamorphism and aqueous alteration) on their parent bodies. A petrographic classification scheme for secondary processes divides the chondrites into 6 types - types 3 to 6 reflect increasing thermal metamorphism, and types 3 to 1 reflect increasing degrees of aqueous alteration. By convention, the chemical classification is followed by the petrologic one (e.g., CI1, CM2, CV3).

Chondritic IDPs, those with roughly chondritic bulk compositions, can be divided into two broad categories (*Bradley*, 2003), compact hydrous particles and porous anhydrous particles often referred to as chondritic porous (CP) IDPs. The hydrous particles share many mineralogical similarities with the CM and CI chondrites. The anhydrous particles do not seem to have an affinity to any known meteorite class. Based on their very fine grain size, disequilibrium assemblage of minerals and amorphous silicates, and abundant presolar materials, the CP-IDPs are thought to be the most primitive Solar System objects found to date. It has been argued that most CP-IDPs are cometary because of their high inferred atmospheric entry velocities (*Joswiak et al.*, 2000). The Stardust mission that recently returned samples of comet Wild II should help establish whether CP-IDPs are indeed cometary.

4.1.3 Major components of meteorites - The chondrites are principally made up of three components – chondrules, refractory inclusions and matrix – whose relative abundances vary widely. Refractory inclusions are a diverse group of objects with sizes that range from a few micrometers to centimeters across and abundances that range from <0.1 to 13 vol.% (*MacPherson*, 2003). They are enriched in the most refractory elements (e.g., Ca and Al) in the canonical condensation sequence. Refractory inclusions formed at high temperatures, some by melting of pre-existing material, others by condensation from a cooling gas. Their conditions of formation are somewhat uncertain, but most probably formed at ~1700-1800 K on timescales of hours to days in a system of roughly solar composition. They are the earliest Solar System objects preserved in meteorites. Most models assume that refractory inclusions formed sunward of the asteroid belt and were transported to the asteroid belt via an X-wind or through turbulent diffusion.

Chondrules are the most abundant objects in most chondrites (up to ~80 vol%) (*Connolly*, 2005). They are ~0.1-1 millimeter-sized silicate and metal/sulfide spherules that formed by partial or complete melting of solid precursors. They experienced peak temperatures of ~1700-2100 K and formed on timescales of minutes to hours (cooling rates of ~10-1000 K/hr) in environments that were probably enriched in dust relative to gas by factors of ~100-1000 compared to solar. There is considerable debate about when and how chondrules formed. However, it seems that the chondrules in at least some chondrites formed 1-2 Myr after refractory inclusions. Currently, the most popular mechanism for chondrule formation is in shockwaves in the asteroid belt, although other explanations such as the X-wind model have not been ruled out.

The fine-grained matrix cements the chondrites together and makes up 10-50 vol.% of most chondrites (*Huss et al.*, 2005). Matrix abundance in CI chondrites may have been 90-100 vol.%, but they have been so extensively aqueously altered that their primordial matrix abundances remain uncertain. Because of its fine grain size and relatively high volatile element contents, matrix is generally assumed to be more primitive than chondrules and refractory inclusions, an assumption that is confirmed by the presence of presolar materials in it (see Section 4.3). Matrix shares some similarities with IDPs, and it is in matrix and IDPs that we are most likely to find evidence for the thermally annealed dust.

Most of the least atmospheric entry heated CP-IDPs are enriched relative to CI in volatile elements (*Kehm et al.*, 2002; *Flynn et al.*, 2004). The average major element compositions of IDPs are also fractionated (Fig. 2). The major and trace element fractionations may result either from preferential destruction of coarser/denser more refractory IDP material during atmospheric entry, or because like most chondrites there has been loss of more refractory material during processing in the nebula (*Alexander*, 2005).

4.2 Causes of element fractionations in chondrites

The correlation between elemental abundances in chondrites and volatility (Fig. 1) clearly points to the role of thermal processes in generating the fractionations. The most widely accepted explanation for the fractionations has been that they reflect variations in conditions during cooling and condensation of an initially totally vaporized inner solar nebula (*Wasson and Chou*, 1974; *Bland et al.*, 2005). The continuous variation in abundance of moderately and highly volatile elements with condensation temperature in chondrites (Fig. 1) requires a more-or-less continuous process of separation of condensates from the gas (*Cassen*, 2001). Variations in the more refractory element abundances seem to be associated with the addition of refractory inclusions to CM, CV and CO chondrites, and loss of refractory material from most other chondrites (Figs. 1 and 2).

An alternative explanation for the elemental fractionations is the so-called two-component model (e.g., *Alexander*, 2005). In this model, the moderately and highly volatile element abundances of chondrites were largely determined by mixing of volatile-rich, primitive matrix and volatile-depleted chondrules and refractory inclusions. The presence of presolar materials in the matrix of all chondrites in roughly CI abundances shows that the chondrites did accrete a primitive matrix component. Most problematic for the two-component model is the fact that bulk matrix compositions are not CI-like, but the addition of a few tens of percent of more refractory material to matrix and secondary redistribution of elements during parent body processes might explain this.

A third class of explanations are motivated by the rough complementarity between refractory element depletions in the gas of the diffuse ISM and the volatile element depletions in the chondrites (*Palme*, 2002; *Huss et al.*, 2003; *Yin*, 2005). The models suggest that the fractionations in chondrites were largely the result of sublimation of volatile-rich ices and amorphous material inherited from the presolar molecular cloud. Hence, the volatile element fractionations in meteorites should resemble those in the dust in the diffuse ISM. However, the CI chondrites are unfractionated although they are not composed of unprocessed interstellar material (see Section 4.5), and these models cannot explain all the elemental fractionations seen in chondrites, or the isotopic systematics of radiogenic systems (e.g., U-Pb and Rb-Sr) in which the parent and daughter have very different volatilities (*Palme*, 2002).

4.3 Presolar materials

While most components of chondrites and IDPs formed in the Solar System, they also contain presolar materials that were inherited from the protosolar molecular cloud. These materials include circumstellar grains (formed around evolved stars) and interstellar organic matter. Interstellar grains (formed in the ISM) and grains from YSOs must be present, but it has proved to be much more difficult to definitively identify them. The presolar materials potentially retain a record of thermal processing in the solar nebula and also could act as tracers of unaltered primordial dust abundances.

4.3.1 Circumstellar grains - The major types of circumstellar grain found to date include nanodiamonds, silicates, SiC, Si_3N_4, graphitic spherules and oxides. Based on their isotopic compositions, the circumstellar grains mostly formed around RGB and AGB stars, with a few percent from supergiants, supernovae and, possibly, novae (e.g., *Zinner*, 2003; *Clayton and Nittler*, 2004). Circumstellar graphitic grains are highly underabundant in meteorites compared to Galactic dust production rates (*Alexander*, 2001). Indeed, graphite and poorly graphitized C of any origin are rare in chondrites and IDPs, which is inconsistent with some diffuse ISM dust models. The major carbonaceous components are organic matter and nanodiamonds. Nanodiamonds have been tentatively identified in circumstellar outflows (*Hill et al.*, 1998), may be very abundant in the ISM (*Allamandola et al.*, 1993; *Jones and d'Hendecourt*, 2000), and have been observed in one protoplanetary disk (*Habart et al.*, 2004b).

To date, five presolar silicate grains have been examine in the TEM to determine their major element compositions and mineralogies (*Messenger et al.*, 2003, *2005*; *Nguyen et al.*, 2005). Contrary to astronomical expectations, two of them were crystalline forsteritic olivine, and one of these is a supernova grain (*Messenger et al.*, 2005). This compares with 0.2±0.2% crystalline silicates in the diffuse ISM (see Section 2.2) and the inferred high enstatite/forsterite ratio in stellar outflows (see Section 2.1). Neither of the olivine grains shows evidence for having been irradiated, although the supernova grain is composed of multiple subgrains and may have been annealed.

With the exception of ~1% of highly disordered grains, the SiC is highly crystalline with little evidence for radiation damage (*Daulton et al.*, 2003; *Stroud et al.*, 2004b; *Stroud and Bernatowicz*, 2005). The larger pristine SiC grains (≥0.5 μm) show little evidence for sputtering or cratering (*Bernatowicz et al.*, 2003). Smaller SiC grains found in acid residues are more irregular in shape (*Daulton et al.*, 2003), but whether this is the result of grain growth, ISM processing or the harsh chemical treatments used to isolate them is not known. The size distribution of SiC in meteorites is consistent with the inferred size distribution around C-stars (*Russell et al.*, 1997).

Stroud et al. (2004a, 2005) reported detailed studies of two Al_2O_3 grains and two hibonite ($CaAl_{12}O_{19}$) grains. The hibonite and one of the Al_2O_3 grains were crystalline, while the other Al_2O_3 grain was amorphous. *Stroud et al.* (2004a) argued that the grains that survive in meteorites "were not significantly processed by radiation in the ISM" and that the differences in microstructure of the two Al_2O_3 grains reflect conditions during condensation in the AGB outflows.

It seems likely that the circumstellar grains found in meteorites and IDPs avoided processing in the diffuse ISM. Direct injection of dust from AGB stars, etc., into molecular clouds is rare (*Kastner and Myers*, 1994) and cannot explain the 10s to 100s of sources that are represented in the circumstellar grains (*Alexander*, 2001). There is no evidence that the circumstellar grains have protective layers, of organics for instance, that are thick enough to have protected them from grain-grain collisions in ISM shocks (*Bernatowicz et al.*, 2003). SiC grains >0.5 μm can largely survive (≤10% loss) an ISM shock provided that the shock speed lies between ~50-80 km/s (*Slavin et al.*, 2004). Graphite and silicate grains can also largely survive provided that they are >1 μm and shock speeds fall in much more restricted ranges. The much more restricted range of conditions over which graphite and silicate grains survive shocks means that they should be underabundant relative to SiC, particularly at grain sizes of <1 μm. Graphite is underabundant (*Alexander*, 2001). Circumstellar silicate abundances are still rather uncertain, but almost all the grains found to date are <1 μm. Perhaps the best explanation is that stochastic processes result in a small fraction of grains only spending a short time in the diffuse ISM and/or only encountering shocks that do not significantly affect them.

4.3.2 Interstellar organics - The organic matter in chondrites can be divided into soluble and insoluble fractions (*Gilmour*, 2003). The soluble fraction has been intensively studied, but the insoluble organic material (IOM) makes up the majority >75% of the organic material in chondrites. The large D and ^{15}N isotopic enrichments in IOM in chondrites and IDPs are thought to be the result of ion-molecule reactions and other ISM processes (e.g., *Messenger*, 2000; *Aléon et* *al.*, 2001), although D enrichments in gas-phase molecules are possible in the outer solar nebula (*Aikawa et al.*, 2002). There are variations in the isotopic composition of IOM within and between chondrites and IDPs, but this may reflect parent body processing in chondrites (*Alexander et al.*, 1998) and atmospheric entry heating of IDPs (*Keller et al.*, 2004). The most primitive meteoritic IOM at least isotopically resembles the IOM in IDPs (*Busemann et al.*, 2005), and has an elemental composition ($C_{100}H_{75}N_4O_{15}S_4$) that is similar to the average composition ($C_{100}H_{80}N_4O_{20}S_2$) of comet Halley CHON particles (*Kissel and Krueger*, 1987). Thus the organics in meteorites, CP-IDPs and comets appear to be related despite their parent bodies' very different formation conditions and locations.

Further evidence in favor of the IOM's presolar origins is found in the similarity between the 3-4 μm infrared (IR) spectrum of the IOM and the refractory organic matter in the diffuse ISM (*Pendleton et al.*, 1994). The IOM may also be partly responsible for the ubiquitous 2175 Å UV absorption feature in the diffuse ISM (*Bradley et al.*, 2005). This would be consistent with the inference of *Adamson et al.* (1999) that the carriers of the 3-4 μm and 2175 Å features share many of the same characteristics.

The IOM is composed of 50-60% of small PAHs (<C_{20}) and 40-50% short, highly branched aliphatic chains (e.g., *Sephton et al.*, 2004; *Cody and Alexander*, 2005). Of the models for refractory organics in the diffuse ISM (see Section 2.1), this most closely resembles that of *Pendleton & Allamandola* (2002), although their PAHs are larger (C_{20-200}) and more abundant (~80%).

4.4 Composition and microstructure of IDPs

Presolar and primitive solar materials are preserved in the matrices of chondrites (*Huss et al.*, 2005). However, the abundance of presolar material in chondrite matrices are not as high as in CP-IDPs, and no chondrites have entirely escaped parent body processing that will have modified or destroyed the finest grained silicates. Hence here we only consider CP-IDPs.

CP-IDPs contain Mg-rich crystalline silicates (mostly enstatite and forsterite), equilibrated aggregates (EAs), amorphous silicates largely in the form of GEMS (glass with embedded metal and sulfide), and IOM (*Bradley*, 2003). Crystalline silicates are a major (~20-50 vol%) component of anhydrous IDPs and occur as single crystals ranging in size from 0.1μm to several μm, as well as in polycrystalline aggregates with constituent grain sizes <0.5 μm. They are typically enstatitic pyroxene and forsteritic olivine (Mg/(Mg+Fe)>0.95), although they can be more Fe-rich and other minerals are present. The microstructure (multiple twins and intergrowth of ortho- and clino-polymorphs) of much of the pyroxene (Fig. 3) suggests that it formed by condensation at temperatures above 1258 K (*Bradley et al.*, 1983) and cooled relatively rapidly. There has been no systematic study of the pyroxenes with this microstructure. The cooling rate, estimated from the ~20-25 vol% of ortho-enstatite in one grain (*Bradley et al.*, 1983) and the experiments of *Brearley et al.* (1993) is ~1000 K/hr, but clearly more work needs to be done. A similar microstructure is seen in chondrule pyroxenes and chondrules are thought to have cooled at ~10-1000 K/hr. So-called enstatite whiskers and rods seem to be metastable condensates that cannot be used for cooling rate estimates (*Bradley et al.*, 1983). The pyroxene/olivine ratio varies considerably between IDPs. The pyroxene-rich ones are generally considered to be more primitive because in a small sample they tended to be more C-rich (*Thomas et al.*, 1993), but forsterite seems to dominate in comets (see Section 2.4).

Crystalline silicates also occur in EAs that are a common minor (<10 vol%) component of CP-IDPs (Fig. 4). These μm-sized aggregates contain numerous grains of enstatite, pyrrhotite ($Fe_{1-x}S$), minor forsterite, and an interstitial amorphous Si-rich phase. The textures, mineralogy and mineral chemistry of EAs are consistent with the annealing of GEMS precursors at T≥1000 K for hours (*Brownlee et al.*, 2005). A continuum of morphologies is observed from porous to solid GEMS to EAs that probably reflect a sequence of thermal annealing at subsolidus temperatures (below the thermal stability limit of pyrrhotite) in the nebula. The presence of the Si-rich amorphous phase as a by-product of the annealing is consistent with IR observations of protoplanetary disks that invoke a Si-rich component to fit the 10 μm silicate feature of the processed silicates (e.g., *Bouwman et al.*, 2001).

GEMS grains are <0.5 μm in diameter and consist of numerous 10 to 50 nm-sized Fe-Ni metal and Fe-Ni sulfide grains dispersed in a Mg-Si-Al-Fe amorphous silicate matrix (Figure 5). The FeO contents of GEMS are very low, in contrast to what has been inferred for ISM dust (see Section 2.2). *Keller et al.* (2005) have demonstrated that most GEMS grains are aggregates composed of even smaller subgrains (<100 nm) exhibiting strongly heterogeneous chemical compositions. GEMS grains are systematically sub-solar (~0.6 x solar) with respect to S/Si, Mg/Si, Ca/Si, and Fe/Si (*Keller and Messenger*, 2004), although the average Al/Si ratio in GEMS is indistinguishable from solar.

Bradley (1994) proposed that GEMS are preserved interstellar silicates, based primarily on O excesses and Mg depletions at the edges of GEMS that they attributed to preferential sputtering. Other irradiation experiments have found that O is depleted along with Mg (see Section 3.2). *Bradley et al.* (1999) also showed that there is a close resemblance in the IR spectra of GEMS and interstellar silicates. *Westphal and Bradley* (2004) propose that GEMS grains are the products of intense irradiation in fast (~1000 km/s) shocks of initially crystalline circumstellar grains from supergiant stars in OB associations. However, the presolar grains and most dust production estimates suggest that supergiants are minor contributors of dust to the ISM (see Sections 2.2 and 4.3). Also, the O elemental enrichments in GEMs and lack of vesicles are contrary to expectations from most irradiation experiments, although the metal could be the result of irradiation-induced reduction. The model predicts that ultimately there is almost complete replacement of the original atoms by the implanted shock gas. Both the original supergiant grains and the shock gas, which is highly enriched in supernovae ejecta, will be isotopically very anomalous in O. Yet within the measurement errors, <1-5% of GEMS have demonstrably non-solar O isotopic compositions, and most that are anomalous probably formed around AGB stars (see Section 4.3). The only supernova silicate grain found to date is crystalline.

One explanation for the lack of vesicles and roughly solar isotopic compositions would be if GEMS were ISM condensates. *Keller and Messenger* (2004) point out that on average GEMS compositions are not consistent with average diffuse ISM dust – relative to Si their Mg, Fe and Ca contents are too low and their S contents are too high. They estimate that only 10-20% of GEMS have roughly diffuse ISM-like dust compositions, while the remaining 80-90% are probably Solar System in origin. Condensates that formed in the ISM or in YSO outflows may be present, but if their isotopic anomalies are small they would not have been recognized. Even with isotopically anomalous silicate/oxide grains, it may be difficult to distinguish between circumstellar and YSO grains under some circumstances. *Keller et al.* (2005) also argue that the heterogeneous chemical compositions of the GEMS subunits are at odds with uniform chemical gradients expected from extensive irradiation, and that GEMS are more likely to be the result of coagulation of compositionally distinct subgrains that formed during fractional condensation, probably in the solar nebula (*Keller et al.*, 2005).

However, there is a conflict between a Solar System origin for most GEMS and an interstellar origin for the IOM. The IOM would be destroyed at high temperatures. Consequently, if most crystalline material and most GEMS are solar condensates, no more than 10-20% of the original presolar IOM should remain in IDPs. Yet, the IOM content of IDPs is ~40-70% of that expected of ISM dust, which is roughly consistent with their crystallinity (see Section 4.5). Either a higher fraction of the GEMS must be interstellar, or much of the IOM is Solar System in origin.

4.5 Constraints on the thermal processing of dust

The crystalline material in IDPs is dominated by what appear to be solar nebula condensates, with lesser amounts of annealed GEMS heated to ≥1000 K. The microstructure of much of the pyroxene in IDPs seems to require relatively rapid cooling from above 1258 K. The IOM would be destroyed or heavily modified by temperatures of ≥1000 K. Therefore, if the IOM is interstellar, its abundance is a useful indicator of the degree of thermal processing, particularly in the chondrites where parent body processes have modified much of the fine-grained material.

Assuming that all Mg was condensed in dust and there have not been any dust fractionations, the solar-normalized C/Mg ratios give the fractions of the total C in refractory organics in the dust formation regions. The estimated fraction of C in refractory organics in comet Halley dust, including the quoted possible factor of two error, is in the range 1-0.3 (*Jessberger and Kissel*, 1991; *Schulze et al.*, 1997), in the CP-IDPs is ~0.35 (*Schramm et al.*, 1989; *Thomas et al.*, 1993), and in CIs is 0.07 (*Alexander et al.*, 1998). Roughly 15% of the original IOM in CIs may have been destroyed by aqueous alteration (*Cody and Alexander*, 2005). Halley dust has a crystallinity of ~50%. If this crystallinity reflects the fraction of material that has been thermally processed, the original fraction of C in refractory organics in dust from the presolar molecular cloud would have been ≥0.6. The abundance of refractory organics in dust in molecular clouds has not been determined directly. In the diffuse ISM, assuming that all C-rich dust is organic (including PAHs), ~50% of the total C is in the organics (*Zubko et al.*, 2004) and ~80% if the *Lodders* (2003) solar composition is adopted.

The low abundance of IOM in CI chondrites may be due to >75-85% of the original dust having been thermally processed. If it was the result of thermal processing, somehow it was done without significantly fractionating the more volatile elements because the CI and solar abundances are very similar (*Lodders*, 2003). This means that gas and dust cannot have fractionated from one another during the thermal processing (evaporation/condensation and annealing), perhaps because the dust was fine-grained enough for it to remain coupled to the gas. The difference in IOM abundance between chondrites, CP-IDPs and comets suggests that there was a gradient in the dust processing in the solar nebula. How steep the gradient was will depend on where the CP-IDPs formed.

Scott and Krot (2005) have suggested that dust processing could have occurred during chondrule formation. However, the abundance of IOM in matrix is roughly CI-like in all primitive chondrites, and apparently unrelated to chondrule or refractory inclusion abundances. The CI chondrites contained few if any chondrules or refractory inclusions, yet they have much lower IOM contents than CP-IDPs or comets. There is not evidence for chondrule fragments in CP-IDPs, although this could reflect a bias because larger, denser particles are more intensely heated during atmospheric entry. Finally, the lack of large isotopic fractionations in chondrules suggests that they formed as stable melts (e.g., *Davis et al.*, 2005). In this case, it is unlikely that the gas would have overcome kinetic barriers to nucleation and condensed as small isolated crystals rather than condensed directly onto the already existing chondrules. At present, it seems unlikely that the crystalline dust in CP-IDPs is the direct product of chondrule formation. Also, the evidence from chondrules and CAIs is that volatile elements were lost during their formation.

5. MODELING OF GRAIN HEATING IN PROTOPLANETARY DISKS

5.1 During accretion onto the disk

Infalling dust from the molecular cloud envelope surrounding a forming stellar system will be heated first by radiation from the central star and disk, and subsequently at the accretion shock. *Chick and Cassen* (1997) modeled the heating grains would experience during infall onto the disk. The results depend on the model assumptions, but they conclude that grain temperatures would never exceed 1000 K beyond ~1.5 AU, and that refractory organics would survive beyond 0.5-4 AU depending on the conditions. Since most material will accrete onto the disk beyond 4 AU, infall heating is an unlikely explanation for the crystallinity of silicates beyond the terrestrial planet region or the variations in refractory organic abundances between chondrites, IDPs and comets.

5.2 Shocks

At radial distances out to ~5-10 AU, heating in shocks generated by disk instabilities or the giant planets are sufficient to anneal grains and possibly vaporize small ones (<0.25 μm) (*Harker and Desch*, 2002). Oort cloud (long period) comets are thought to have formed at 5-10 AU and then been scattered into the Oort cloud by Jupiter. Thus, shock heating could explain the high fraction of crystalline material in Oort cloud comets without requiring vigorous radial mixing. Shock heating would also be consistent with the relatively rapid cooling required by the CP-IDP pyroxene microstructures (see Section 4.4). Since small grains will remain coupled to the gas while they are being heated, it is possible that shock heating could anneal or vaporize and recondense grains without producing volatile element fractions. However, shock heating cannot explain the high crystallinity of 9P/Tempel 1 (see Section 2.4), a Kuiper belt comet, unless there was vigorous transport of dust in the disk or some Kuiper belt objects formed in the giant planet region. The same is true if CP-IDPs are mostly from Kuiper belt comets (see Section 4.1.1).

5.3 Radial transport in disks

Radial transport of dust from the hot inner portions of a disk is another explanation for the high crystallinity of silicates in comets (*Nuth et al.*, 2000b). The distances that material must be transported will depend on the stage of disk evolution. For typical T Tauri disks with low accretion rates, the estimated midplane temperatures range from about 1500 K inside about 0.2 AU, to about 300 K at 1 AU (e.g., *D'Alessio et al.*, 2001). During periods of significantly higher mass accretion, midplane temperatures are expected to be correspondingly higher, with temperatures exceeding 1000 K at 1-5 AU under some conditions (*Boss*, 1998; *Bell et al.*, 2000).

Outward flow of material near the midplane of disks with return flow in the upper regions of the disk, turbulent diffusion and large-scale motions associated with spiral arms could all contribute to the transport of some matter from the inner to the outer portions of a disk on reasonable timescales (*Gail*, 2001; *Bockelèe-Morvan et al.*, 2002; *Boss*, 2004; *Gail*, 2004). This could possibly explain observations of crystallized silicates in comets, but the timescales for cooling of condensed grains in these large-scale motions are likely to be too slow to explain the microstructures of crystalline pyroxene in CP-IDPs (see Section 4.3).

Gail (2002) also models the destruction of refractory organic C as primordial dust is transported within a disk. The abundance of refractory C increases with increasing radial distance, and at any given radial distance the abundance depends on the mass accretion rate. Qualitatively these results are consistent with the relatively low C content in chondrites (including CIs) compared to comets and IDPs. The models suggest that the low C contents of chondrites forming at 2-3 AU would require high accretion rates ($>10^{-6}$ M_o/yr), but it is not clear whether the refractory C remaining has been heated significantly. The many similarities between the IOM in chondrites (~2wt%) and CP-IDPs (5-40 wt%) suggest that the chondritic material has not been heated significantly. Analysis of the IOM by pyrolysis GC-MS is usually carried out by heating the sample to ~873 K for a few seconds. Experiments by *Cody et al.* (in preparation) also find that heating at 873 K for even a few seconds significantly affects the IOM.

6. SUMMARY

The relative abundances of circumstellar grains in meteorites broadly conform to astronomical estimates, with most coming from AGB stars, although the abundance of graphite/amorphous C in meteorites is lower and nanodiamonds higher than expected. The relative abundances of supernova grains are only of the order of a few percent, which is much lower than some estimates or upper limits. It seems likely that the circumstellar grains preserved in meteorites avoided processing in the ISM.

The evidence for interstellar material in meteorites is less clear. Many properties of the IOM in meteorites and IDPs are consistent with an interstellar origin, but whether synthesis of similar materials in protoplanetary disks is possible has yet to be determined. The evidence for an interstellar origin for GEMS is a matter of debate. Many of the properties of GEMS are consistent with an interstellar origin. However, their often high S contents and lack of evidence for implanted H and He seem to be inconsistent with GEMS being highly irradiated interstellar grains. Within the measurement uncertainties, <1-5% of GEMS have non-solar O isotopic compositions. Some GEMS may be condensates, probably of Solar System origin, although at present interstellar and YSO origins cannot be excluded. If most GEMS are Solar System condensates, the crystallinity of IDPs underestimates the degree of thermal processing and most IOM must be solar.

The crystalline fraction of CP-IDPs is dominated by Solar System condensates, with lesser amounts of annealed GEMS. The microstructure of the pyroxene suggests that it formed above 1258 K and then cooled relatively fast (~1000 K/hr). Because the IOM would be modified or destroyed at temperatures >1000 K, provided that it is interstellar its abundance is a useful additional indicator of the degree of thermal processing. In CP-IDPs, the IOM abundance is about 40-70% of estimates of the ISM dust organic content. This is roughly consistent with the 20-50% silicate crystallinity in CP-IDPs. The IOM content in CI chondrites is much lower than this. Thus, there probably was a gradient of thermal processing in the Solar System, but how steep it was depends on the origin of the CP-IDPs (outer main belt asteroids or comets). Whatever the mechanism for thermal processing of dust, it did not result in the loss of the volatile elements, perhaps because the dust was fine-grained enough to remain coupled to the gas as it cooled.

Models show that radial transport of material from the hot inner nebula out to distances of 10s of AU is possible on reasonable timescales. However, the cooling rates in the inner nebula may be too slow to explain the microstructure of pyroxene in IDPs that require cooling rates after formation of ~1000 K/hr. Shock heating predicts faster cooling times. Shock heating is unlikely to be strong enough to anneal/vaporize dust beyond ~10 AU. If crystalline material in Kuiper belt objects was produced by shock heating, an efficient mechanism for radial transport in the outer Solar System is still required. Shock heating is also the currently most favored mechanism for making chondrules. Chondrule formation was probably not directly responsible for thermal processing of dust. However, it is possible that IDP dust processing and chondrule formation were driven by the same mechanism and occurred at the same time but in different places – dust processing occurred in regions of lower dust density with few large grains (e.g., above the midplane in the asteroid region and/or at >3-4 AU).

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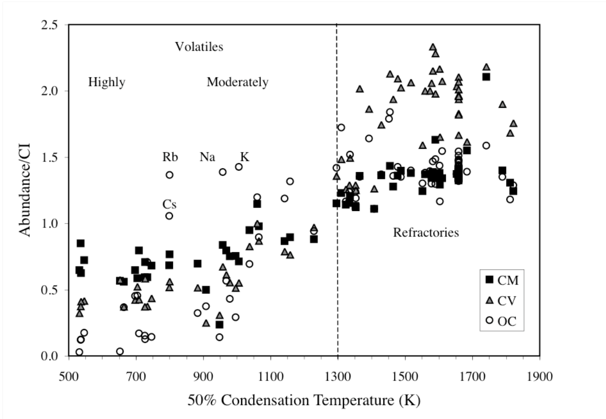

Figure 1. The CI normalized elemental abundances vs. 50% condensation temperature (*Lodders*, 2003) in three chondrite groups (*Wasson and Kallemeyn*, 1988) showing the volatility dependence of the elemental fractionations

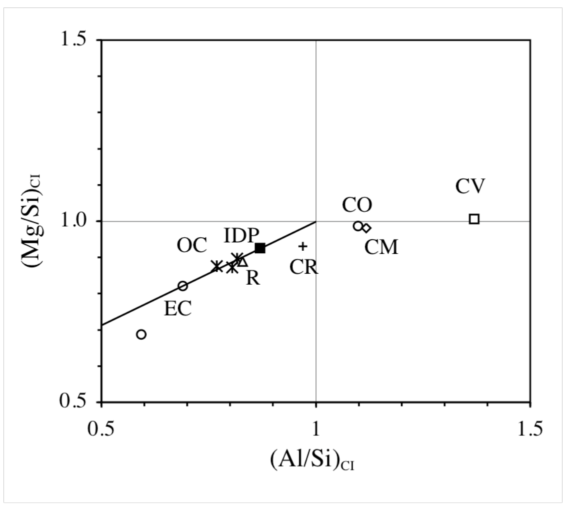

Figure 2. The CI-normalized Mg/Si vs. Al/Si elemental ratios of bulk chondrites (*Wasson and Kallemeyn*, 1988) and anhydrous, CP-IDPs (*Schramm et al.*, 1989; *Thomas et al.*, 1993). The OC, EC, R, CR chondrites, as well as the CP-IDPs all form a trend that is probably linked to the loss of refractory material. The CO, CM and CV chondrites form a distinct trend that may be due to addition of refractory inclusions.

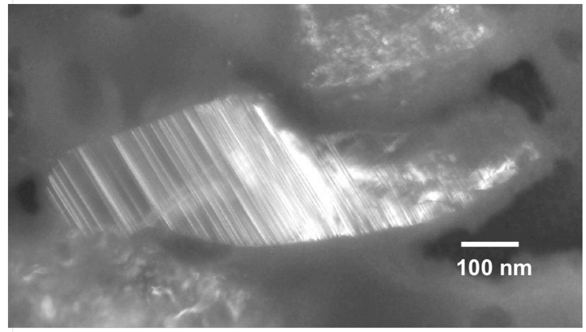

Figure 3. A typical isolated enstatite grain from a chondritic porous IDP. The fine lamellae are the result of relatively rapid cooling through the protoenstatite-orthoenstatite (1258 K) transition (*Bradley et al.*, 1983)

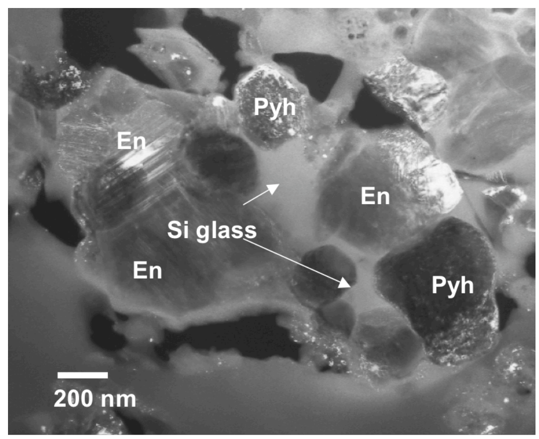

Figure 4. An annealed aggregate in a CP-IDP composed of enstatite (En: $MgSiO_3$) and pyrrhotite (Pyr: $Fe_{1-x}S$) set in a SiO_2-rich glass.

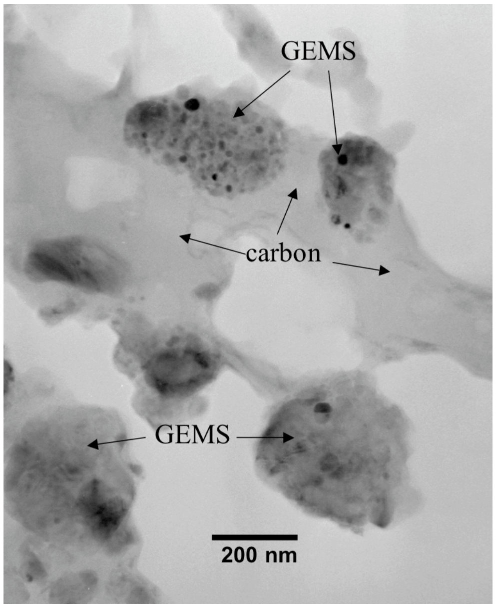

Figure 5. GEMS from a CP-IDP set in an organic carbon matrix. The GEMS are polymineralic objects. The dark sub-grains are mostly Fe-Ni metal and Fe sulfide.