ARE THERE CLUES TO THE DUST 'ANNEALING' PROCESS IN PROTOPLANETARY DISKS IN IDPS? C.M.O'D. Alexander[1] and L.P. Keller[2], [1]DTM, Carnegie Institution of Washington (alexande@dtm.ciw.edu), [2]NASA Johnson Space Center (lindsey.p.keller1@jsc.nasa.gov).

Introduction: Silicate dust in the interstellar medium (ISM) is almost entirely amorphous [1]. However, dust at the surfaces of protoplanetary disks has crystallinities of 10-95%, and at least in some cases this crystallinity decreases with increasing distance from the central star [2]. This 'annealing' of ISM dust requires temperatures of at least 1000 K, and is clear evidence that an energetic process is operating in these disks.

There is ample evidence in meteorites and IDPs for high temperature processes operating in the early Solar System. It is possible that one of these processes is also responsible for the crystallinity of dust in protoplanetary disks. Based on similarities in their IR spectra, chondritic porous interplanetary dust particles (CP-IDPs) are the best analogs available for the dust in protoplanetary disks. Here we review the properties CP-IDPs and their components to determine whether they hold clues to the process responsible for the 'annealing'.

Components: Crystalline silicates are a major (~20-50 vol%) component of anhydrous IDPs and occur as single crystals ranging in size from 0.1 μm to several μm, as well as in polycrystalline equilibrated aggregates (EAs) with constituent grain sizes of <0.5 μm [3]. The other major components are amorphous silicates, largely in the form of GEMS (glass with embedded metal and sulfide), and insoluble organic matter (IOM) [3].

The single crystals are typically almost pure enstatite and forsterite. The microstructure of the enstatite suggests that it formed by condensation and, at least in the case of platelets, at temperatures above the proto-orthopyroxene transition (1258 K) [4]. The single olivines are also assumed to be condensates. The enstatite/forsterite ratio varies considerably between IDPs, but forsterite seems to dominate in comets. In the equilibrium condensation sequence, pyroxene forms by reaction between olivine and SiO_2 in the gas. However, there is no evidence for this reaction in IDPs, and the enstatite probably condensed directly from the gas [4]. Whether forsterite or enstatite formed may simply have reflected the conditions (e.g., temperature) at which grain formation became possible.

Crystalline silicates also occur in EAs that are a common minor (<10 vol%) component of CP IDPs. 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 [5].

GEMS grains are the other major silicate component of CP-IDPs. GEMS grains are <0.5 μm in diameter and consist of numerous 10 to 50 nm-sized FeNi metal and Fe-Ni sulfide grains dispersed in a Mg-Si-Al-Fe amorphous silicate matrix. Most GEMS grains are aggregates composed of even smaller subgrains exhibiting strongly heterogeneous chemical compositions [6]. GEMS grains are systematically sub-solar (~0.6xsolar) with respect to S/Si, Mg/Si, Ca/Si, and Fe/Si [7], although the average Al/Si ratio in GEMS is indistinguishable from solar.

Bradley [8] proposed that GEMS are preserved interstellar silicates, and [9] showed that there is a close resemblance between the IR spectra of GEMS and interstellar silicates. While still rather uncertain, ≤1-5% of GEMS have demonstrably non-solar O isotopic compositions, that suggests they are circumstellar rather than interstellar in origin [10]. At present, there appears to be little that petrologically distinguishes the isotopically anomalous (circumstellar) GEMS from other GEMS. Also, on average GEMS compositions are not consistent with estimates of average ISM dust compositions [7]. Only 10-20% of GEMS have roughly ISM-like dust compositions, and [7] suggest that the remaining 80-90% are probably Solar System condensates.

The IOM can constitute 5-40 wt% of CP-IDPs. The presence of large D and ^{15}N hot spots in IDP IOM has long been taken as evidence that much or all of it formed in the ISM. The IR and UV absorption properties of the IOM are consistent with this. However, recent calculations suggest that large D enrichments can develop in gas phase molecules in protoplanetary disks [11]. At present it is not known whether significant synthesis of IOM can occur in the disks. Nevertheless, an interstellar origin for the IOM is not as certain as was once thought.

Discussion: The IOM would be destroyed or heavily modified by temperatures of ≥1000 K. If the IOM is interstellar, its abundance is an indicator of the degree of thermal processing. Assuming that all Mg was condensed in dust, the solar-normalized C/Mg ratio gives the fraction of the total C in organics in the formation regions of primitive objects. The estimated fraction of C in IOM in the CP-IDPs is ~0.35 [12, 13], and in CIs is 0.07 [14]. In the diffuse ISM, assuming that all C-rich dust is organic, ~70% of the total C may be in the organics [15]. Thus, if CP-IDPs formed from interstellar

material, their IOM content is consistent with their ~50% crystallinity. However, if GEMS are largely solar condensates, the IOM abundance is much too high for it to be interstellar in origin. Also, the low abundance of IOM in CI chondrites suggests much greater thermally processing than IDPs. Yet CI chondrites appear to be less elementally fractionated than CP-IDPs.

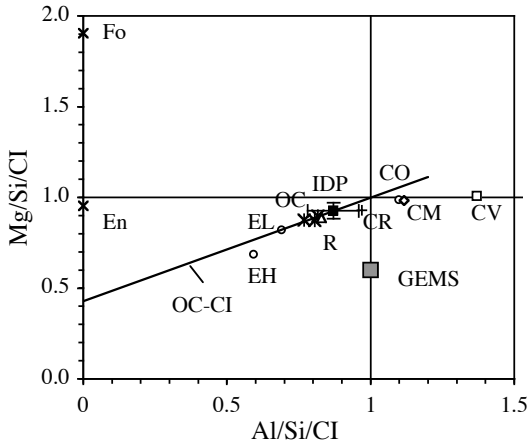
Despite the apparent primitiveness of CP-IDPs their bulk silicate major element compositions are fractionated relative to CI [12, 13]. For instance, in Fig. 1 the average CP-IDP composition falls on the same Mg/Si-Al/Si mixing line as the CI, OC, EC, and R chondrites. In addition, volatile elements in CP-IDPs may be enriched relative to CI [16].

At present, there is little evidence for a significant difference between CI and solar [17]. Thus, a refractory-rich, volatile-poor component must have been fractionated from CP-IDPs. If the single olivines and pyroxenes in IDPs formed by condensation from a solar gas, they must have formed along with refractory-rich and volatile-rich condensates. The compositions of these components will have varied depending on whether forsterite or enstatite was the dominant condensate. GEMS alone would not complement either forsterite or enstatite (Fig. 1). It seems that there must be at least one additional unidentified Al-rich phase in CP-IDPs.

Heating mechanism: Two mechanisms have been suggested for producing the 'annealing' in protoplanetary disks – shock and transport of dust from the hot inner disk. These two processes predict very different cooling rates for the dust. The ~20-25% orthopyroxene that enstatite platelets contain [4, and unpublished] indicate cooling rates of ~1000 K/hr [18]. Such rapid cooling rates suggest that shock heating was the mechanism for thermal processing of IDPs. Shocks are naturally produced by giant planets and/or by a gravitationally unstable disk from which planets may rapidly form. Thus, if the crystallinity in protoplanetary disks was produced in the same way as IDPs, this has important implications for our understanding of the evolution of these disks.

Shock heating may also have produced chondrules, so chondrule formation may be responsible for thermal processing of IDPs and dust in protoplanetary disks [19]. However, the abundance of IOM in matrix is roughly CI-like in all primitive chondrites, and apparently unrelated to chondrule or CAI abundances. The CI chondrites contained few if any chondrules or CAIs, yet they have much lower IOM contents than CP-IDPs or comets. Consequently, it is unlikely that the crystalline material in IDPs, comets and protoplanetary disks are the direct products of chondrule formation. However, both may be the products of the same shock wave generating mechanism.

Conclusions: The higher crystallinity of dust in protoplanetary disks compared to the ISM reflects energetic processes operating in disks. The IR spectra of comets and CP-IDPs that may come from comets resemble the IR spectra of dust in protoplanetary disks. The crystallinity and IOM contents of CP-IDPs are consistent with them being mixtures of thermally processed and unaltered interstellar material. Cooling rates estimated from the microstructures of enstatite grains suggest that the thermal processing was the result of shock heating. However, the uncertain origins of GEMS and elemental fractionation in CP-IDPs raise important questions about this explanation for the origin of CP-IDPs.



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