THE NATURE AND ORIGIN OF INTERPLANETARY DUST: HIGH TEMPERATURE COMPONENTS.
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Introduction. The specific parent bodies of individual interplanetary dust particles (IDPs) are unknown, but the anhydrous chondritic-porous (CP) subset has been linked directly to cometary sources [1]. The CP IDPs escaped the thermal processing and water-rock interactions that have severely modified or destroyed the original mineralogy of primitive meteorites. Their origin in the outer regions of the solar system suggests they should retain primitive chemical and physical characteristics from the earliest stages of solar system formation (including abundant presolar materials). Indeed, CP IDPs are the most primitive extraterrestrial materials available for laboratory studies based on their unequilibrated mineralogy [2], high concentrations of carbon, nitrogen and volatile trace elements relative to CI chondrites [3, 4, 5], presolar hydrogen and nitrogen isotopic signatures [6, 7] and abundant presolar silicates [8].

Chondritic-porous IDPs. Typical CP IDPs are highly porous particles that consist of fine-grained crystalline silicates, GEMS (glass with embedded metal and sulfides) grains, and Fe-Ni sulfides, all encased by an organic-rich carbonaceous matrix. The constituent grains in IDPs are much finer-grained (<1 μm) than typical meteorite matrix grains. The abundance of glassy grains (e.g. GEMS grains) is also much higher in IDPs than in meteorite matrix.

Crystalline silicates in CP IDPs are predominantly olivine and low-Ca pyroxene, with lesser high-Ca pyroxene, feldspar, and rare melilite. Multiple lines of evidence suggest a high temperature nebular condensation origin for most of the crystalline silicates in CP IDPs. The olivine and pyroxene grains are typically single crystals and have Mg-rich (Mg/Mg+Fe ~ 100-90) and Mn-rich (up to 5 mol%) compositions that are consistent with condensation models [9]. Many of the enstatite grains and some of the forsterite crystals show unique whisker and platelet morphologies (Figure 1) as well as characteristic defects (axial screw dislocations) that implicate growth from the vapor phase [10]. The crystalline silicates observed in CP IDPs also show marked similarities in terms of mineralogy, size, composition, and abundance to those observed forming around young stars and in comets through astronomical infrared (IR) spectroscopic measurements [11, 12]. Additional evidence that the crystalline silicates are an early-formed component of CP IDPs includes: 1) the presence of pre-accretionally irradiated rims on many of the crystalline grains which indicates the grains were exposed as small objects prior to their accretion into their parent bodies and 2) the close association of crystalline silicates with presolar molecular cloud materials (high D/H organics) and presolar silicates.

Presolar forsterite grains have been identified in CP IDPs on the basis of their oxygen isotopic compositions. One forsterite grain appears to have originated from red giant or asymptotic giant branch (AGB) stars [8]. We have recently identified a group of polycrystalline forsterite grains whose O isotopic compositions point toward an origin from a type II supernova [13].

GEMS Grains. GEMS grains are a major component of CP IDPs and are <0.5 μm diameter grains consisting of abundant 10 to 50 nm-sized kamacite and Fe-Ni sulfide grains dispersed in a Mg-Si-Al-Fe amorphous silicate matrix (Figure 2). To date, GEMS grains have not been reported from any meteorite samples. Bradley [2] proposed that GEMS are preserved interstellar (IS) silicates based on observed preaccretional irradiation effects and IR spectral properties that closely resemble IS dust [14]. Oxygen isotopic measurements confirm that at least a small fraction (<5%) of GEMS are demonstrably presolar, while the remainder have ratios that are indistinguishable from solar values [8, 15].

GEMS with solar oxygen isotopic compositions either had their isotopic compositions "homogenized" through processing in the interstellar medium (ISM) [e.g. 16], or formed in the early solar system. We have recently measured bulk elemental compositions of GEMS grains and showed that they are systematically sub-chondritic with respect to S/Si, Mg/Si, Ca/Si, and Fe/Si [17]. For these element/Si ratios, the average GEMS compositions are ~60% of solar values, although the average Al/Si ratio in GEMS is indistinguishable from solar. The elemental and isotopic data for GEMS grains suggest that most formed in the early solar nebula either as shock melts or as direct, non-equilibrium condensates [17]. In this model, the pre-accretional irradiation effects observed in GEMS grains occurred in the solar nebula – this view is supported by the similar magnitude of irradiation effects experienced by GEMS grains and many of the crystalline silicates in CP IDPs. If most GEMS grains are condensates, then a mechanism has to exist to transport the GEMS grains (as well as some forsterite and enstatite) to the comet-forming region, perhaps through bipolar outflows during the early accretion phase of the disk [16].

Trace components. High temperature refractory phases such as those observed commonly in Ca- and Al-rich inclusions (CAIs) in meteorites also occur in

IDPs [18-20] however, the average grain size is much smaller than is observed in CAIs [19]. Fassaite, anorthite, gehlenite, spinel occur as rare isolated grains in chondritic IDPs, but entire IDPs dominated by CAI-like mineralogy are also observed [18,19].

Sulfides. Sulfides are a major constituent of CP IDPs and dominated by low-Ni pyrrhotites with a wide range of grain sizes [21]. The pyrrhotites occur as isolated single crystals as well as 10-50 nm-sized grains decorating the exterior of GEMS grains. The sulfides are believed to result from the sulfidation of pre-existing FeNi metal in the early nebula. Observational evidence suggests that Fe sulfides are likely circumstellar grains around young stars [22], although isotopically anomalous sulfides have not been detected in preliminary S isotopic measurements [23].

Discussion CP IDPs derive from fundamentally different parent bodies than meteorites. Their most probable sources are short-period comets that originate from the Kuiper belt. These particles thus sample an entirely different regime of the solar nebula, ~40 AU from the Sun, than meteorites (1.8-3.5 AU). These IDPs contain abundant crystalline grains that must have formed at high temperatures, predominantly in the solar system (as shown by their isotopic compositions). Most GEMS grains are similarly solar in O isotopic compositions and their origins appear to be linked with the solar system crystalline silicates based on complementary chemical signatures [17]. Both the crystalline silicates and GEMS are intimately mixed with thermally labile presolar organic matter. These observations are most easily explained by a substantial portion of IDP components originated in high-temperature processes near the Sun, and were subsequently transported to the Kuiper belt. Such extensive radial mixing of material in young stellar objects has been inferred from observations of bipolar outflows.

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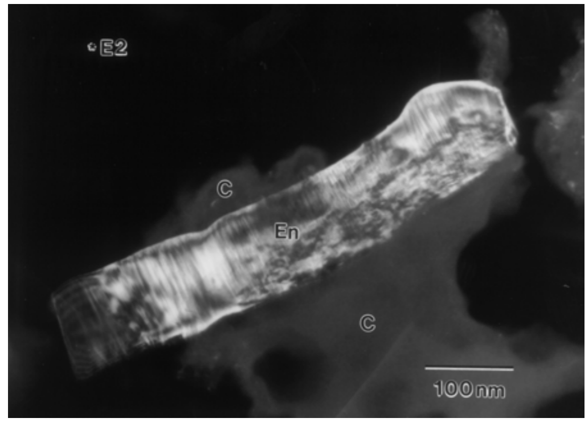

Figure 1. A darkfield transmission electron image of an enstatite whisker in IDP L2009*E2. Characterisitic elongation direction is perpendicular to the (100) stacking faults.

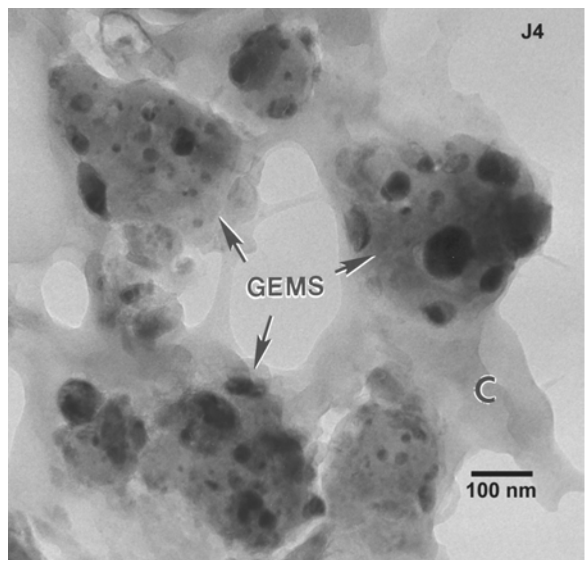

Figure 2. A brightfield TEM image of a cluster of GEMS grains and their carbonaceous matrix (L2009J4). The dark, rounded grains within the GEMS are kamacite and FeNi sulfide grains.