FROM GRAIN FORMATION TO DUST AGGREGATION IN THE SOLAR PROTOPLANETARY DISK: THE RECORD PRESERVED IN CHONDRITIC POROUS INTERPLANETARY DUST PARTICLES.

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Introduction: Chondritic porous interplanetary dust particles (CP IDPs) from comets and asteroids, collected by NASA from the Earth's stratosphere, are unequilibrated aggregates of mostly submicron mineral grains. CP IDPs (Fig. 1) range from ~5 to ~25 µm in size and each has a major element composition roughly the same as that of the CI meteorites (i.e., "chondritic"). Most CP IDPs show no evidence of significant post-accretional parent body alteration, which overprints the record of formation processes in meteorites. CP IDPs never experienced significant hydrous or thermal parent body processing, gravitational compaction, or impact shock, and many were minimally heated during atmospheric deceleration. As a result, CP IDPs are the most cosmochemically primitive astromaterials available for laboratory study [1], making them ideal materials to examine to decipher the record of processes that occurred in Solar Protoplanetary Disk from grain formation to dust aggregation.

Disk Processes: The Solar System is believed to have begun ~4.6 billion years ago with the gravitational collapse of part of a giant molecular cloud having an elemental composition that was preserved in the Sun, a composition very similar to "chondritic" for the condensable elements. As the cloud collapsed the rotation rate increased and the central region became hotter.

Condensation of Minerals: The equilibrium condensation temperatures of mineral grains in the Solar Protoplanetary Disk were modeled by Lodders [2] using Solar element abundances and a gas pressure representative of conditions at 1 AU. The results indicate that the first mineral to condense as a gas of Solar composition cools is corundum, at 1677 K, followed by other Al-Ti-oxides, with spinel condensing at 1397 K [2]. The first silicate to condense is gehlenite, at 1529 K, but most of the Si is removed from the gas at lower temperatures, with anorthite forming at 1397 K, followed by forsterite at 1354 K, enstatite at 1316 K, and diopside at 1347. Iron condenses into metal alloy at 1357 K, which further interacts with the Nebular gas to form scheribersite at 1248 K and triolite at 704 K [2]. Magnetite forms at an even lower temperature (371 K).

Each CP IDP is roughly chondritic, but no individual mineral in the condensation sequence has a chondritic composition, indicating each CP IDP is an aggregate of a variety of minerals that formed diverse temperature conditions. Transmission Electron Microscopy shows individual CP IDPs are dominated by olivines and pyroxenes having a wide range of Mg/Fe ratios, Fe- and Zn-Fe-sulfides, glass with embedded metal and sulfides (GEMS), and contain a variety of minor mineral phases. A few phases preserve non-solar isotopic ratios, indicating they are pre-Solar grains that survived disk processing.

The more than 600 K diffference between the formation temperature of silicates (olivine and pyroxene) and the much lower temperature of formation of the Fe-sulfides indicates that these minerals do not form at the same place at the same time. If grain aggregation occurred easily in the formation region then aggregates of silicates, devoid of lower temperature sulfides, would be expected in the dust. But the CP IDPs are well mixed aggregates incorporating phases that formed over a wide range of disk conditions. Some contain phases produced under widely differing oxygen fugacities, the most striking being Fe-metal and Fe-bearing silicates in the same particle [3]. The diversity of CP IDP mineralogy indicates aggregation was inhibited in the region where minerals were condensing.

Some minerals, e.g. Zn-Fe-sulfides with a sphalerite structure, provide evidence for non-equilibrium formation, since the lowest energy assembly results in Fe-sulfide with a interatomic spacing too small to accomodate Zn, so Zn would form a separate Zn-sulfide.

Although CP IDPs have roughly chondritic abundances of Al [4] and Ti [5], the high temperature Al-Ti-oxides are not found in abundance in the CP IDPs. If Al and Ti had condensed into oxides in this region of the disk but were not incorporated into the CP IDPs, CP IDPs would be deficient in Al and Ti. This suggests the formation of Al- and Ti-oxides was inhibited in the region of the disk sampled by the CP IDPs, and Al and Ti were incorporated into other lower temperature phases, possibly indicating that the formation region of the silicates and sulfides found in CP IDPs was never hot enough for the formation of these oxides..

Grain Transport: If, as suggested by modeling, the CP IDPs are predominately cometary dust [1], the mineral grains must be transported from the warm inner disk, where the high temperature minerals likely formed, to a cooler region, farther from the center of the disk, wherer the comets are believed to have formed. The size-frequency distributions of the Mg-rich silicates (olivine and pyroxene) and Fe-sulfides show a size-density relationship in different CP IDPs consistent with aerodynamic sorting operating in the disk prior to grain aggregation [6], suggesting aerodynamic transport of the crystalline mineral grains from the warm inner disk to a region where grains from different formation environments were mixed together. A later study that included the GEMS grains confirmed the silicate and sulfide sorting trend, but found that, the GEMS size data do not exhibit any clear relationship to the crystalline components, indicating that the GEMS were not sorted along with the silicate and sulfide crystals [7]. This suggests that the GEMS formed in a different environment than the crystalline minerals, but were mixed with the crystalline minerals before grain aggregation.

Organic Grain Coatings and Dust Aggregation: Modeling [8] shows ultraviolet and thermal processing of ice coated grains in the cold, outer Solar Nebula can produce complex organic molecules. A diverse variety of individual grains, including silicates, sulfides, and carbonates, in many CP IDPs are rimmed with a thin coating of organic matter (Fig. 2), ~100 nm thick, independent of the grain composition [9]. X-ray Absorption Near-Edge Spectroscopy of these organic grain demonstrates the presence of C, N, and O, with N:C and O:C ratios significantly higher than the ratios in meteoritic insoluble organic matter suggestive of very primitive organic matter [10]. Both C=C and C=O functional groups were identified [10]. These organic rims confirm the modeling of Ciesla and Sandford [8] providing evidence for the formation of organic matter early in the evolution of the Solar Protoplanetary Disk, after grain formation but before the these grains aggregated into dust. These organic rims likely aided in aggregation, since bare mineral grains can stick only in very low speed collisions, while organic coatings are expected to increase the range of sticking speeds [11].

Conclusions: While many details remain to be uncovered, the CP IDPs record a sequence of events beginning with mineral condensation in a warm region of the Solar Protoplanetary Disk, above the formation temperature of forsterite and enstatite but possibly not hot enough for the formation of Al- and Ti-oxides. This region cooled to <700 K, allowing formation of sulfides. Grain aggregation was inhibited in this region. These mineral grains were transported outward, a result consistent with inferences from the Wild 2 particles collected by Stardust [12], by a process that size sorted the grains in a manner consistent with aerodynamic transport, to a cooler region of the disk. In this region amorphous silicate grains (GEMS) were added, and the grains were well mixed. They were then coated with organic matter that likely aided in aggregation, producing dust particles that have been preserved with minimal alteration in the CP IDP parent body. The structure and composition of the CP IDPs provides constraints on the processes operating in the Solar Protoplanetary Disk that aid in constraining models of the disk.

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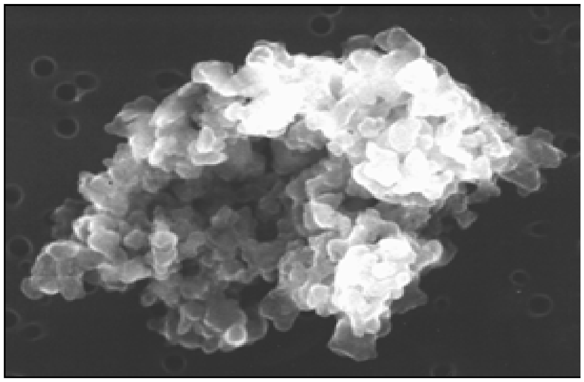

Figure 1: Scanning electron microscope image of an ~11 µm chondritic IDP collected from the Earth's stratosphere by a NASA aircraft. The individual surface features are micron or submicron grains that have aggregated to form this dust particle. (NASA photo)

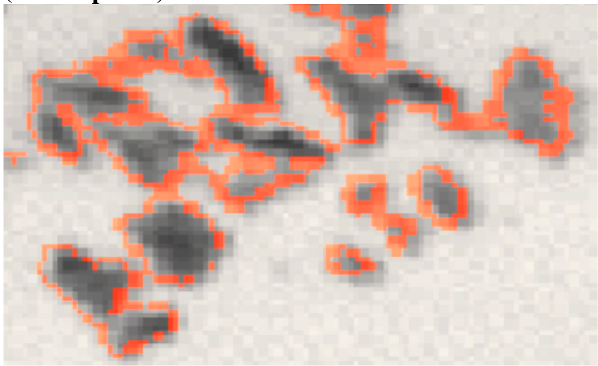

Figure 2: High-resolution (~25 nm per pixel) x-ray absorption image of part of an ultramicrotome slice of a CP IDP, L2011*B6, showing the individual micron- and submicron-size mineral grains (dark gray). An image of the organic matter selected by cluster analysis (red) is superimposed, showing that the ~100 nm thick rims of organic matter form the contact surfaces between the individual mineral grains. (Field of view ~2.5 µm wide.)