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Organic grain coatings in primitive interplanetary dust particles: Implications for grain sticking in the Solar Nebula

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The chondritic porous interplanetary dust particles (CP IDPs), fragments of asteroids and comets collected by NASA high-altitude research aircraft from the Earth's stratosphere, are recognized as the least altered samples of the original dust of the Solar Nebula available for laboratory examination. We performed high-resolution, $\sim$25 nm/pixel, x-ray imaging and spectroscopy on ultramicrotome sections of CP IDPs, which are aggregates of $>10^4$ grains, and identified and characterized $\sim$100 nm thick coatings of organic matter on the surfaces of the individual grains. We estimated the *minimum* tensile strength of this organic glue to be $\sim$150 to 325 N/m^2, comparable to the strength of the weakest cometary meteors, based on the observation that the individual grains of $\sim$5 μm diameter aggregate CP IDPs are not ejected from the particle by electrostatic repulsion due to charging of these IDPs to 10 to 15 volts at 1 A.U. in space. Since organic coatings can increase the sticking coefficient over that of bare mineral grains, these organic grain coatings are likely to have been a significant aid in grain sticking in the Solar Nebula, allowing the first dust particles to aggregate over a much wider range of collision speeds than for bare mineral grains.

Key words: Interplanetary dust particles, grain sticking, grain aggregation, organic matter.

1. Introduction

Many of the processes that occurred early in the history of our Solar System have not yet been definitively established. The first step in the formation of asteroids, comets and planets is believed to have been the aggregation of submicron and micron size grains into dust particles in the early Solar System. Blum and Wurm (2008) noted that: "The process by which submicrometer-sized protoplanetary dust particles evolve to kilometer-sized planetesimals is still enigmatic." This process of grain aggregation in the early Solar System is reviewed in detail by Cuzzi and Weidenschilling (2006).

There are three possible outcomes of collisions between grains: hit and stick, hit and bounce, or hit and fragment. Only the first of these outcomes leads to aggregation of the individual grains into dust particles. Collision experiments conducted in Earth's gravity indicate that bare rocky particles bounce apart at collision speeds less than 30 to 50 m/s and shatter each other at higher speeds (Hartmann, 1978). For grain aggregation to occur for very small objects, where the mutual gravitational force is inconsequential, there must be a mutual attractive force, such as the van der Walls force or some other type of surface energy, electrostatic or magnetic force, and/or some mechanism to dissipate energy in the collision.

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Modeling of the sticking coefficient for micron-size, bare silicate grains suggested sticking would occur only for collision speeds less than 5 cm/s (Dominik and Tielins, 1997). However, collision experiments conducted in micro gravity in a drop tower, using micron-size SiO_2 spheres showed that aggregation occurred for collision speeds <1.2 m/s, aggregation and fragmentation were roughly in balance for speeds from 1.2 to 1.9 m/s, and fragmentation dominated for speeds >1.9 m/s (Blum and Wurm, 2000).

But mineral grains do not condense into spheres, so many of the dust grains of the early Solar System are believed to have been irregularly shaped, rather than spherical. Microgravity experiments indicate that at speeds up to $\sim$1.9 m/s aggregation of irregularly shaped grains can occur, but higher speeds result in fragmentation (Blum and Wurm, 2000). Thus, it seems likely that, at extremely low speeds (<2 m/s) in low or zero gravity, surface forces, like the van der Waals, electrostatic or magnetic forces discussed in Cuzzi and Weidenschilling (2006), can promote grain aggregation. Since grains impact over a broad range of speeds in the Solar Nebula, grain growth occurs only for speed distributions where the rate of aggregation exceeds the rate of fragmentation.

Dust aggregation experiments by Blum *et al*. (2006) using irregularly shaped SiO_2 grains resulted in aggregates with a high porosity (0.93). Dust samples consisting of these polydisperse, irregular SiO_2 grains showed a range of tensile strengths, peaking at $\sim$250 N/m^2, while the tensile strength of samples of quasi-monodisperse, irregular diamond grains peaked at $\sim$200 N/m^2 (Blum *et al*., 2006).

Both of these samples were described as "slightly compressed," with porosities of 0.83 for the SiO_2 grains and 0.78 for the diamond grains. The tensile strength increased significantly with the degree of compression of the material, rising to 2300 N/m^2 for the irregular SiO_2 grains compressed to a porosity of 0.56 (Blum *et al.*, 2006), so uncompressed samples of these materials are likely to have tensile strengths somewhat lower. The uncompressed porosity for the irregular SiO_2 grains was 0.93 (Blum *et al.*, 2006), significantly higher than the 0.83 and the 0.56 for the samples on which the tensile strength was determined. To infer the tensile strength of the uncompressed material formed in Blum *et al.*'s (2006) experiments, we performed a linear extrapolation of the pair of data points they reported for the irregular SiO_2 grains. But this approach gave a negative value of the tensile strength for uncompressed, irregular SiO_2 grains (i.e., porosity = 0.93), demonstrating that a linear fit is not appropriate but indicating that the uncompressed material has a tensile strength substantially lower than 250 N/m^2. A second degree polynomial fit, which requires a third point, was performed including as the third point zero tensile strength at a porosity of 1. This second degree polynomial fit gives a tensile strength at a porosity of 0.93, the value for the natural, uncompressed irregular SiO_2 grains formed in Blum *et al.*'s (2006) experiments, of $\sim$50 N/m^2. This porosity is comparable to that of the most porous interplanetary dust particles (IDPs), extraterrestrial dust collected intact from the Earth's stratosphere (Flynn and Sutton, 1991).

The critical collision speed at which fragmentation begins to dominate over aggregation is sensitive to the porosity, surface structure, and composition of the grains. Collision experiments described in Kudo *et al.* (2002) and Kouchi *et al.* (2002) performed on particles coated with laboratory analogs of interstellar organic matter found that these coated grains stuck together quite easily, even at collision speeds up to 5 m/s, an order-of-magnitude higher than the speed at which silicate-based or ice-based grains accreted due to the weak surface forces under the same conditions. At a temperature of 300 K Kudo *et al.* (2002) determined the tensile strength of these organic-coated particles to be $\sim 10^3$ N/m^2. The experimental results of Kudo *et al.* (2002) indicate that it is desirable to examine the surfaces of the grains that were present in the Solar Nebula at the time of grain aggregation to determine if they were bare silicates or if they had organic coatings. If they had organic coatings, then we could employ the same techniques we used to characterize organic matter in the IDPs (Flynn *et al.*, 2003) to investigate the nature of these surface coatings to determine if they could have aided in grain aggregation by increasing the critical collision speed where aggregation exceeds fragmentation. To do this, we first must identify the appropriate samples, those that contain the primitive submicron- and micron-size grains of our Solar System in an unmodified form.

2. Samples

Meteorites sample the primitive material of our Solar System, but all known meteorites exhibit evidence of gravitational compaction, aqueous processing, and/or thermal processing on their parent bodies. The processing experienced by chondritic meteorites and the effects of this processing on the composition and mineralogy of the meteorites is discussed in detail in Brearley and Jones (1998) and Krot *et al.* (2006). These parent body processing events overprinted the record of grain aggregation in the Solar Nebula in all known meteorite samples. Comets may preserve the record of primitive grain aggregation, because comets are believed to have preserved primitive grains in cold storage, well below the temperature where water is liquid, significantly reducing the effects of thermal and aqueous processing. But the only well-identified particles from a comet that are available for laboratory study, the grains of Comet 81P/ Wild 2 collected by the NASA Stardust spacecraft, were captured by $\sim$6 km/s impact into silica aerogel (Brownlee *et al.*, 2006). This process, in which the particles were decelerated from 6 km/s to rest in distances of millimeters to a few centimeters, disaggregated, dispersed, and flash melted most of the fine-grained assemblages identified in the aerogel walls of bulbous deceleration tracks (Leroux, 2012). The surfaces of many of the larger grains were abraded or thermally altered to a depth of $\sim$1 μm (Brownlee *et al.*, 2012), making most of the comet Wild 2 particles unsuitable for the study of original grain surfaces.

IDPs, which are small fragments from asteroids and comets, incident on the Earth's atmosphere at speeds in excess of 10 km/s, are decelerated relatively gently compared to the comet Wild 2 particles collected by Stardust. The IDPs decelerate over distances of 10 km or more, in the Earth's upper atmosphere, and then settle towards the ground. Modeling of the atmospheric entry and deceleration demonstrates that some small particles experience minimal entry heating and alteration (Whipple, 1950; Flynn, 1989; Love and Brownlee, 1994).

NASA has collected small ($\sim$2 to $\sim 50^+$ μm) IDPs from the Earth's stratosphere using U2, ER-2 and WB-57 aircraft since the 1970's (Brownlee, 1985). These IDPs are mostly dust from comets and asteroids. Two types of IDPs—anhydrous IDPs and hydrous IDPs—are present in the stratospheric collections (Fraundorf *et al.*, 1982; Brownlee, 1985; Rietmeijer, 1998). The hydrous IDPs experienced aqueous processing on their parent bodies, overprinting the record of early Solar System processes. Among the anhydrous IDPs, one subgroup, the chondritic porous (CP) IDPs, show no evidence of either thermal or aqueous processing (Ishii *et al.*, 2008).

A typical $\sim$10 μm CP IDP, like the one shown in Fig. 1, is an aggregate of more than 10^4 anhydrous grains, mostly sub-micron in size, consisting predominantly of silicates, mostly olivine, pyroxene, glass with embedded metal and sulfide (GEMS), and rarer Fe-sulfide grains. The individual grains of these CP IDPs are unequilibrated (Fraundorf *et al.*, 1982), some exhibit isotopic anomalies indicating they are interstellar/circumstellar grains that survived incorporation into the Solar System (Messenger, 2000), and they have elemental compositions consistent with primitive Solar Nebula material (Brownlee, 1985; Flynn, 1994). These CP IDPs are believed to be unequilibrated aggregates of both the initial condensates of the Solar System and some interstellar grains that avoided homogenization (Ishii *et al.*,

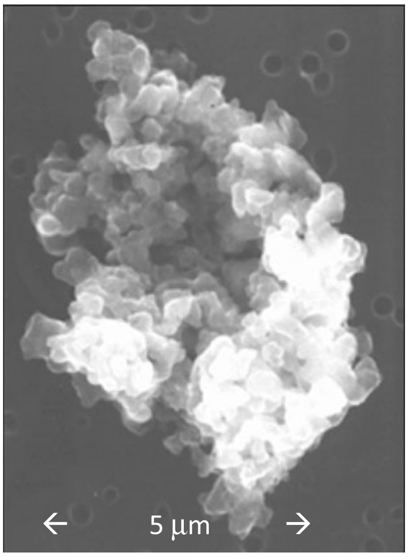

Fig. 1. Scanning electron microscope image of an ∼11 μm chondritic IDP collected from the Earth's stratosphere by a NASA aircraft. The individual surface features are micron or submicron grains that have aggregated to form this dust particle. (NASA photo)

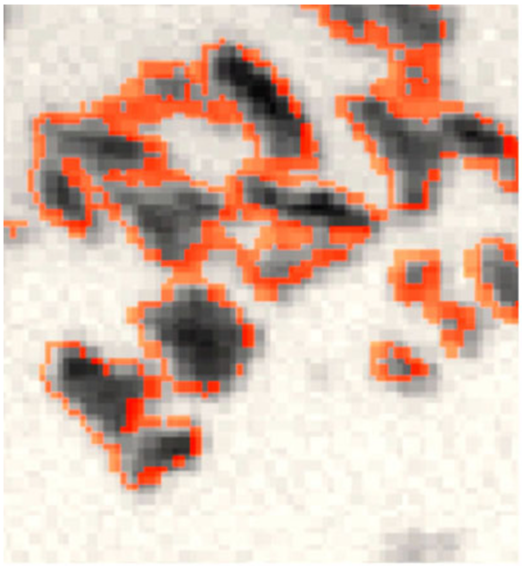

Fig. 2. High-resolution (∼25 nm per pixel) x-ray absorption image of part of an ultramicrotome slice of a CP IDP, L2011*B6, showing the individual micron- and submicron-size mineral grains (dark gray). An image of the organic matter selected by cluster analysis (red) is superimposed, showing that the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

2008). Thus, among all the types of extraterrestrial materials currently available for laboratory analysis, the CP IDPs are the best preserved samples of primitive Solar Nebula material available for laboratory study (Ishii *et al.*, 2008).

The porosity of these CP IDPs can be inferred from measurements of their bulk density. The densities of the CP IDPs range from 0.2 to 0.9 gm/cm^3, with a peak at 0.6 gm/cm^3 (Flynn and Sutton, 1991). But the major components of the CP IDPs are silicates—olivine, pyroxene, and GEMS, each having a bulk density of ∼3.2 to 3.5 gm/cm^3. Thus, the porosities of these CP IDPs must be ∼0.70 to 0.94.

The individual grains in the CP IDPs are generally not in direct contact with each other. Brownlee (1985) noted that most porous IDPs consist of an enormous number of small crystals embedded in amorphous material. More detailed study of this amorphous material showed that many of the individual grains are coated by a ∼50 to 200 nm layer of carbonaceous material (Thomas *et al.*, 1996), as shown in Fig. 2. These carbonaceous coatings were characterized by electron energy loss spectroscopy (EELS) as "amorphous carbon" (Thomas *et al.*, 1996). Flynn *et al.* (2003) reported thin carbonaceous coatings on the mineral grains in CP IDPs, but were unable to characterize this thin carbonaceous material at that time. More recently, Matrajt *et al.* (2012) have also reported carbonaceous coatings on mineral grains in several IDPs.

For this work we analyzed slices from eight CP IDPs, L2005*A3, L2008G12, L2008R15, L2009*E6, L2009D11, L2009H9, L2011R11, and L2011*B6, provided to us by the Cosmic Dust Curatorial Facility at the NASA Johnson Space Center. Since our measurements are performed in x-ray transmission, each sample must be thin enough for ∼300 eV x-rays to penetrate through the sample. So we prepared ultramicrotome slices, from 70 to 100 nm thick, using the procedure traditionally employed to prepare samples for examination in transmission electron microscopes (TEMs), making very thin slices of the material by forcing it over a sharp diamond knife. To avoid having the IDPs fragment they were embedded in elemental S for the microtoming (Flynn *et al.*, 2003), avoiding exposure to the epoxy or other organic embedding media traditionally used in the preparation of TEM sections.

3. Analytical Technique

We have examined the carbonaceous grain coatings in detail using a scanning transmission x-ray microscope (STXM) on Beamline X1A1 of the National Synchrotron Light Source. This beamline, described in Flynn *et al.* (2003), uses a zone plate to focus a monochromatic x-ray beam to an ∼25 nm spot. The sample is mounted on piezoelectric stage that can be moved up-and-down and back-and forth through the x-ray beam. A detector, located behind the sample, records the x-ray flux transmitted through the sample. By rastering the sample through the fixed beam, we obtained an x-ray absorption map at the selected x-ray energy. We collected a sequence of ∼250 of these absorption maps, by stepping the monochrometer over the range from 280 to 310 eV, typically in 0.1 eV steps over the critical energy range from 284 to 300 eV, where distinctive molecular features involving C bonds occur. The maps in this image stack were then aligned using techniques described in Jacobsen *et al.* (2000), and carbon-XANES spectra were derived for each pixel in the image stack. We used "cluster analysis," described in Lerotic *et al.* (2005), to compare the C-XANES spectra from each pixel in an image stack and to select and identify groups having similar spectra. Improvements to this STXM provided the spatial stability necessary to characterize the carbonaceous grain coatings by X-ray

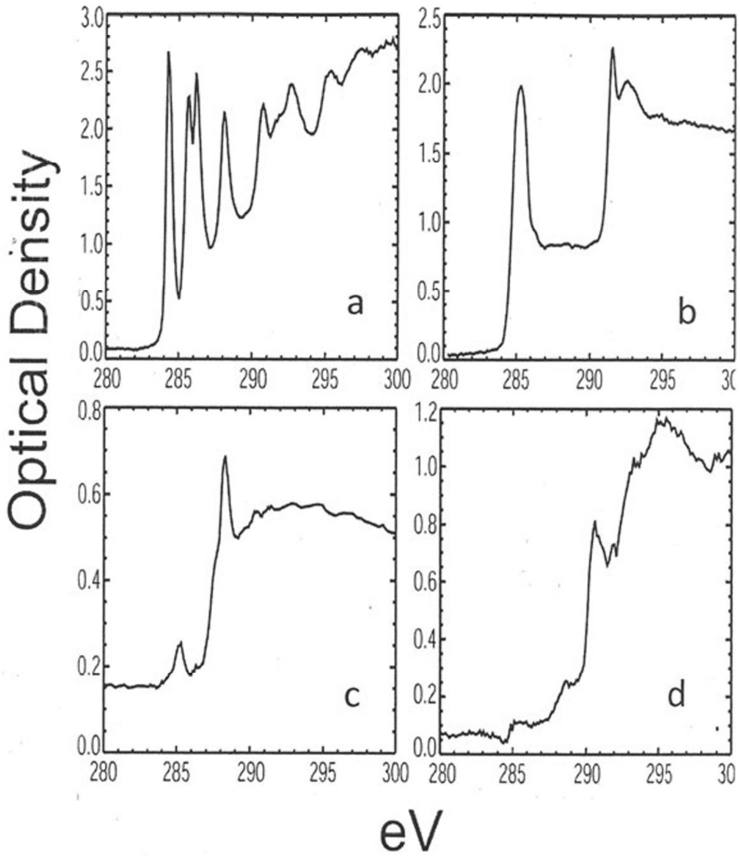

Fig. 3. Carbon XANES spectra of four C-bearing compounds: a) C_{60} fullerenes, b) graphite, c) lysine, and d) formalydehyde.

Absorption Near-Edge Structure (XANES) spectroscopy.

XANES spectroscopy uses x-rays to induce electron transitions from the ground state to unoccupied, higher-energy molecular orbitals. Since these transition energies are characteristic of unique combinations and configurations of these orbitals (i.e. molecular bonds), XANES spectroscopy probes the molecular structure of the material. The XANES spectra were calibrated by measuring CO_2 gas, which has several strong, narrow features in the 280 to 310 eV energy range. Carbon-XANES is particularly useful in distinguishing elemental carbon, such as graphite, amorphous carbon, diamond, or fullerenes, from various types of organic carbon by detecting the characteristic bonding of carbon to H, N, or O in organic matter, as shown in Fig. 3.

4. Results and Discussion

Figure 2 shows an x-ray absorption image of an ultramicrotome slice of a CP IDP, L2011*B6. The structure of the CP IDPs indicates that the carbonaceous material (red) must have been added to the surface of each mineral grain (dark gray) before the assembly of the aggregate dust particle. This implies a three-step sequence for formation of CP IDPs from the Solar Nebula. First, the individual grains condensed from the cooling nebular gas or entered the Solar Nebula in the case of interstellar/circumlstellar grains. Second, the carbonaceous material covered the surfaces of the grains either by deposition, formation in-situ, or a combination of both processes. Finally, the grains collided and stuck together forming the first dust-size material in the Solar System, these CP IDPs. This context establishes the time sequence of the events, but it does not constrain the location(s) in the Solar System where each event occurred.

Each of the CP IDPs we analyzed contains a diversity of carbonaceous material, with most of the CP IDPs having regions that exhibit five or more distinct C-XANES spectra (Flynn *et al.*, 2003). However, when we applied cluster analysis (Lerotic *et al.*, 2005), the program identified most of the carbonaceous grain coatings in each CP IDP as having very similar C-XANES spectra.

In each of the CP IDPs the grain coating was identified as organic, not elemental, carbon by its C-XANES spectrum. The typical C-XANES spectrum of this rim material, Fig. 4, shows two strong pre-edge absorption peaks, one near 285.0 eV, which results from the C=C functional group (Stöhr, 1996), most likely aromatic C-rings, and a second near 288.6 eV, which results from the C=O functional group (Urquhart and Ade, 2002). This identification of abundant C=O spatially associated with the C=C demonstrates that the grain coatings are organic carbon, rather than elemental amorphous carbon. The weaker absorption near 286.5 eV is in an energy range where several functional groups, including phenyl carbon attached to an amide group (Ade and Urquhart, 2002) and carbonyl substituted aromatic (Cody *et al.*, 1998), have absorption features. Since the absorption features from H-bonds are generally weaker than the absorption features from the same number of C=C or C=O bonds, the absence of H-bonding features does not indicate that H is absent from this material. The C-XANES spectra

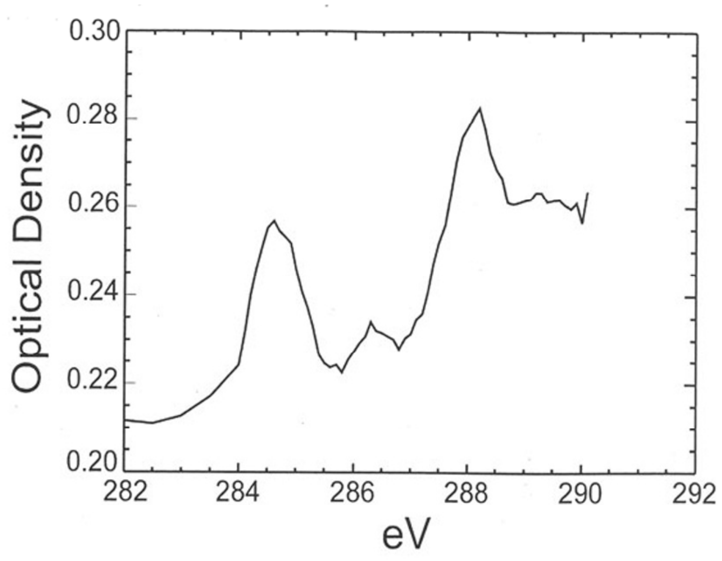

Fig. 4. Carbon-XANES spectrum of the organic rim material in CP IDP L2011*B6, showing the absorption features of C=C (near 285 eV) and C=O (near 288.6 eV).

of these organic grain coatings only provide information on the functional groups present in the rim material. Since the grain coatings are much thinner than the several micrometer diffraction limit for infrared spectroscopy, we have not been able to obtain a more comprehensive characterization of these organic grain coatings by infrared spectroscopy.

We have previously noted that the difference between our identification of organic carbon and the characterization of this material as amorphous carbon in prior EELS analyses likely results from the superior energy resolution of C-XANES, allowing the C=O absorption to be separated from the C K-edge by C-XANES (Flynn *et al.*, 2003), as well as the use of CO_2 for energy calibration in our C-XANES spectrum, allowing a firm energy assignment to the C=O absorption feature. Braun *et al.* (2005) performed a direct comparison of C-XANES and EELS, and confirmed this advantage of C-XANES over EELS.

The organic coatings we have identified on the individual grains of the CP IDPs appear to provide a natural mechanism to first dissipate some kinetic energy during a collision and then glue the grains together. While surface forces, like the van der Waals force, permit sticking at very low collision speeds, the organic coatings we have identified on the surfaces of primitive grains may significantly relax the maximum collision speed requirement for grain aggregation, allowing earlier and more complete grain aggregation in the Solar Nebula. Laboratory collision experiments indicate that grains coated with organic matter stick quite easily, even at collision speeds up to 5 m/s (Kudo *et al.*, 2002). If so, the organic coatings identified on the surfaces of primitive grains likely provide the strength that holds primitive, unprocessed Solar System material (e.g., comets that were not subsequently shocked or heated) together.

It is difficult to directly measure the strength of the organic grain coatings for two reasons. First, the small size, ~10 μm, of the typical CP IDP is well below the capability of normal laboratory instruments. Second, attempting to crush a CP IDP, to determine the crushing strength, frequently distorts the particle into a pancake with the grains remaining attached but slipping in response to the crushing force without producing failure. However, the survival of the CP IDPs under Solar UV bombardment in space, during atmospheric deceleration, and on aircraft impact collection provide indications of the strength of the organic grain coatings.

These small CP IDPs are sufficiently strong to survive the peak dynamic pressure experienced during atmospheric deceleration and the high-speed impact collection by the NASA high-altitude aircraft. The strength required to survive impact collection is difficult to model because of the fractal shape of each CP IDP. However, the peak dynamic pressure experienced by a spherical particle during atmospheric deceleration can be modeled. A 10 μm diameter particle decelerating in the Earth's atmosphere during a normal incidence entry experiences a peak pressure of ~10 N/m^2 (Brownlee, 1985), but much larger CP IDPs survive atmospheric entry intact only to break up on impact collection. Reconstructing some of these "cluster IDPs," so named because they appear as a cluster of small particles on the collection surface, suggest sizes up to 40 to 100 μm in diameter, e.g., a cluster IDP estimated to have a reconstructed size of ~40 μm is described in detail by Thomas *et al.* (1995). An ~100 μm particle decelerating in the Earth's atmosphere during a normal incidence entry experiences a peak pressure of ~100 N/m^2 (Brownlee, 1985), establishing that the largest cluster IDPs must survive dynamic pressures up to ~100 N/m^2.

In addition, a minimum tensile strength can be estimated from the survival of these CP IDPs in space at distances as close to the Sun as 1 A.U., where they encounter the Earth. The observation that many 5 to 20 μm diameter CP IDPs that have been examined by TEM show solar flare tracks (Bradley *et al.*, 1984) and/or solar wind implanted noble gases (Hudson *et al.*, 1981), which penetrate to only hundreds of nm, demonstrates that the current surfaces of these CP IDPs were exposed in space for many thousands of

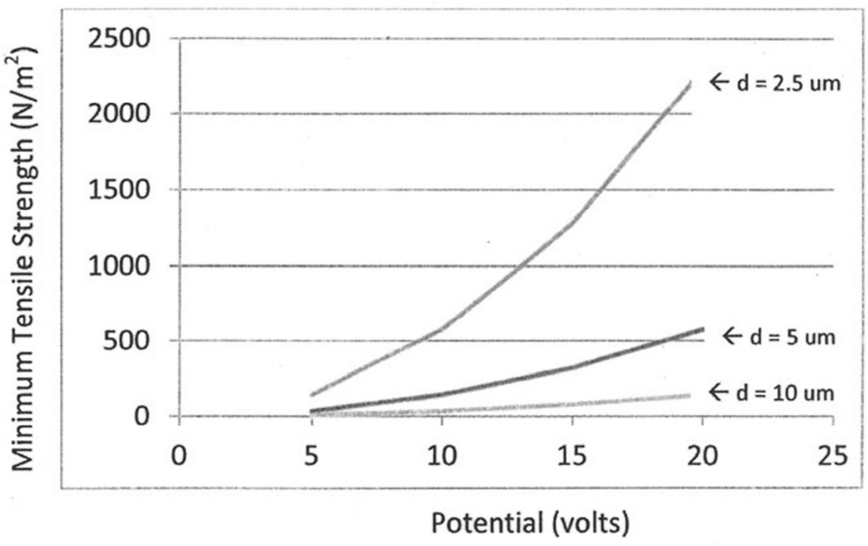

Fig. 5. Minimum tensile strength (N/m^2) required to avoid disruption vs. particle potential (volts) for particles having diameters of 2.5, 5, and 10 μm.

years. Thus these CP IDPs were in space in roughly the size and shape we see them now, and survived in space at 1 A.U. without losing grains from their surfaces due to electrostatic forces.

Unlike the situation for survival under the dynamic pressure of atmospheric deceleration, where the largest particles that survive experience the highest pressure, the observation of survival under solar radiation charging requires higher tensile strength for the smallest particles. The minimum tensile strength of the particle, the strength of the organic coating that connects the individual mineral grains to each other, can be modeled. Solar UV bombardment results in spherical particles near 1 A.U. acquiring a positive charge of ~5 volts by photoelectric emission of electrons (Horanyi, 1996), while modeling including the specific parameters for olivine, a major mineral component in the CP IDPs, indicate that silicate particles acquire a positive charge of 4 to 14 volts at 1 A.U. (Mukai, 1981).

For a sphere having a uniform charge distribution on its surface, as found on a conductor, the minimum tensile strength required so that a grain at the surface is not blown off due to electrostatic repulsion is easily modeled. The total charge Q on the surface of this sphere can be written in terms of the electric potential, "V," of the sphere as:

$$Q = 4V\pi\varepsilon_o r$$

where Q is the total charge on the sphere, ε_o is the permittivity constant (8.85×10^{-12} C^2 N^{-1}m^{-2}), and r is the radius of the sphere. The electric field, "E," at the surface of this sphere is given by:

$$E = Q/4\pi\varepsilon_o r^2 = V/r$$

and the surface charge density σ is given by $\sigma = Q/4\pi r^2 = V\varepsilon_o/r$. The pressure on a small region of the surface, e.g., a grain in the aggregate particle, is given by:

$$P = E\sigma = V^2\varepsilon_o/r^2.$$

Figure 5 shows the electrostatic pressures calculated for particle diameters ranging from 2.5 to 10 μm and surface potentials ranging from 5 to 20 volts. These electrostatic pressures correspond to the minimum tensile strength required so that grains at the surface are not blown off the particle due to electrostatic repulsion. If the tensile strength were lower than this electrostatic pressure some grains would leave the surface, increasing the electrostatic pressure for the now smaller particle, and more grains would be blown off the new surface, resulting in the eventual separation of the entire particle into its individual grains.

A non-conducting sphere of the same size, charged to the same potential, will have the same total charge Q, so some spots on this particle could have higher local charge densities and thus experience even larger electrostatic repulsion forces, requiring a higher minimum tensile strength to prevent the particle from shedding material continuously from the regions having the highest charge.

The survival at 1 A.U. of a spherical particle having a 5 μm diameter and a potential of 10 volts requires a minimum tensile strength of ~150 N/m^2 to avoid breakup under Solar UV irradiation. Overall the collection of 5 to 10 μm CP IDPs that survived in space at 1 A.U. demonstrates that the minimum tensile strength of the organic grain coatings must be ~150 to 325 N/m^2 if the grains are spherical. The 2.5 μm diameter CP IDPs, observed on the collectors, but less well studied because they are more difficult to manipulate and section, require an even greater minimum tensile strength, from 500 to 1200 N/m^2 (Fig. 5), for charges from 10 to 15 volts. Thus, detailed examination of the smallest dust particles on the stratospheric collectors for solar flare tracks or solar wind noble gases could increase the inferred minimum tensile strength of the organic grain coatings significantly.

A non-spherical particle, like most CP IDPs, would reach a higher potential at the same UV flux, thus requiring an even higher minimum tensile strength to survive, ~550 N/m^2 for a 5 μm diameter CP IDP charged to 20 volts (see Fig. 5). Irregularly shaped particles, like the CP IDPs, can have local regions of even higher charge, and aggregates, particularly those including much smaller grains, where secondary electron emission can be important, can reach higher potentials (Ma *et al.*, 2013).

In addition, as shown in Fig. 2, because of the high porosity of the CP IDPs the organic contact points constitute only a small part of the total possible contact surface, requiring that the organic matter be stronger than if it covered the contact surface corresponded to the entire particle cross-section. Thus, the actual tensile strength of the organic grain coatings is likely to be significantly greater than the minimum value calculated in this model.

Observation of meteor fragmentation indicates a tensile strength of $\sim$400 N/m^2 for the weak cometary meteoroids from Comet 21P Giacobini-Zinner (Trigo-Rodriguez *et al.*, 2006). Studies of the tidal disruption of the nucleus of Comet Shoemaker-Levy 9 in Jupiter's gravitational field provide an upper limit on its tensile strength of $\sim$800 N/m^2 (Benz and Asphaug, 1994). Thus our inferred minimum tensile strength of the 5 μm chondritic porous IDPs of $\sim$150 to 325 N/m^2 is comparable to the strength inferred for some of the weak cometary meteors and the nucleus of Comet Shoemaker-Levy 9, and a factor of 3 to 6 higher than the $\sim$50 N/m^2 of the uncompacted, bare silicate studied by Blum *et al.* (2006). In comparison, solid rocks have a tensile strength of $\sim 10^6$ to 10^8 N/m^2, and the tensile strengths of stone meteorites (two carbonaceous chondrites, a variety of ordinary chondrites, and a mesosiderite), summarized by Svetsov *et al.* (1995), range from $\sim 2\times 10^6$ N/m^2 to $\sim 6\times 10^7$ N/m^2, but both terrestrial rocks and these compact meteorites have experienced significant gravitational compaction and thermal metamorphism on their parent bodies.

5. Conclusions

We have observed thin organic coatings on the individual mineral grains of anhydrous CP IDPs, believed to be the least altered samples of the original dust of the Solar System available for laboratory analysis (Ishii *et al.*, 2008). The context indicates that these coatings were produced early in the evolution of the Solar Nebula, after condensation of the first mineral grains but before the aggregation of individual grains into dust particles, the primitive CP IDPs. During atmospheric entry the largest of these IDPs, cluster particles, survive dynamic pressures up to $\sim$100 N/m^2 (Brownlee, 1985), providing a measure of the strength of the organic coating holding the grains together. At the other end of the IDP size spectrum, the minimum tensile strength of the organic coating on a 5 μm CP IDP must be $>$150 to 325 N/m^2 for the particles to have remained intact in space at 1 A.U. under the charging effect of Solar UV bombardment. These minimum values are only slightly lower that the $\sim 10^3$ N/m^2 tensile strength measured by Kudo *et al.* (2002) at a temperature of 300 K, roughly the equilibrium temperature of 5 μm glassy carbon spheres in space at 1 AU (Hanner *et al.*, 1999), for the particular organic mixture they employed, and that tensile strength greatly aided grain sticking compared to bare silicate grains. Kudo *et al.* (2002) reported that the tensile strength of their organic coating increases at lower temperature, peaking at $\sim 10^6$ N/m^2 in the asteroid belt between 2.3 and 3 AU, and then decreases again as the organic becomes rigid at much lower temperatures, far out in the Solar System. Thus, these organic grain coatings are likely to have been particularly important in aggregation of the asteroids. This minimum tensile strength is comparable to the strength determined for some weak cometary meteors, but the actual tensile strength of the organic grain coatings in the CP IDPs is likely to be much greater than this minimum value. Although it has been demonstrated that aggregation of submicron grains will occur at low collision speeds (e.g., Blum and Wurm, 2000), bare silicate grains that were held together only by these weak surface forces are likely to disaggregate under UV bombardment at 1 A.U. Measurements by Blum *et al.* (2006) on compressed silicate aggregates held together only by surface forces, when extrapolated to uncompressed material, which has a density comparable to some CP IDPs (Flynn and Sutton, 1991), suggest the surface forces between bare silicate grains result in a tensile strength of only $\sim$50 N/m^2, a factor of 3 to 6 lower than the minimum tensile strength inferred for the organic grain coatings based on the failure of 5 μm CP IDPs to fragment because of charging when at 1 A.U. in space. These organic grain coatings most likely aided in dust aggregation in the Solar Nebula, providing a cushioning effect and a sticky surface that is likely to have significantly increased the maximum speed at which grain aggregation could occur. This allows earlier and more complete grain aggregation in the Solar Nebula.

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