EVIDENCE FOR THE PRESENCE OF ALIGNED INTERSTELLAR MAGNTITE CORE-DIRTY MANTLE GRAINS IN THE SOLAR NEBULA AND ITS IMPLICATIONS FOR PLANETESIMAL GROWTH.

Z. W. Hu[1] and R. P. Winarski[2], [1]XNano Sciences Inc., P. O. BOX 14294, Huntsville, AL 35815, USA; zwhu@xnano.org. [2]Aadvanced Photon Source, Argonne National Laboratory, Argonne, IL 60439, USA.

Introduction: To make planets in star-encircling protoplanetary disks, solid bodies must first grow over about 10-11 orders of magnitude in size, say, from submicron grains to 1-10 km sized planetesimals [1]. But the details of dust coagulation are poorly understood. In advanced growth-by-sticking models where small grains collide at low relative velocities and stick together via van der Waals forces, dust growth stalls at the bouncing and fragmentation barriers (~ mm-cm or pebble size) [2-3], prohibiting planetesimal formation, for example, via streaming instability (SI) and/or clustering instability (CI). (Both SI and CI would not kick in until the dust reaches ~ cm-dm in size [2-3].) Magnetic grains, on the other hand, may lead to quite a different outcome in dust aggregation as suggested by laboratory study and modelling of model grains [4]. Given that interstellar grains provide the raw material for planetesimal formation, it is essential to pin the nature and properties of interstellar grains down in order to gain insight into how dust grains aggregate in disks. Iron, one of the most abundant elements in the universe, is severely depleted in the interstellar gas phase relative to its solar abundance. Uncovering the whereabouts and form of "the missing iron" is vital to understanding the evolution of the dust that forms primordial planetesimals.

Methods: We noninvasively unlock the structure and properties of primitive (cometary) interplanetary dust particles (IDPs) in 3D nanoscale detail using phase contrast X-ray nanotomography (PCXNT) – a new noninvasive X-ray nano-CT imaging technique that incorporates refraction-based phase-contrast effects into otherwise absorption X-ray nanotomography, enabling pores and low-, medium-, and high-density grains (carbonaceous components, silicates, and Fe-rich minerals) throughout intact IDPs to be mapped morphologically, microstructurally, and mineralogically in a manner that is otherwise unobtainable [5-6]. We identify aligned interstellar grains based on their properties and examine the morphology and growth of the constituent grains and parent particles as a whole – a holistic approach enabled by PCXNT imaging and 3D nanoanalytical methods.

Initial Results: The elongated quasi-ellipsoidal porous IDP (shown in Fig. 1(a)) contains two morphologically distinct types of refractory grains: irregular, elongated grains that represent a major grain population; hollow grains that each have a nanohole running through the core and are morphologically consistent with refractory carbonaceous or organic hollow globules [5]. The elongated grains have long-to-short axial ratios varying from about 2.2 to 3.3, in agreement with a mean aspect ratio (~ 2.87) of the elongated comet 67P grains acquired with Rosetta [7]. Moreover, the elongated grains tend to be aligned along the particle's long axis (e.g., grains A–F, Fig. 1b)) – and they are composite grains containing oriented magnetite nanocrystals as shown in Fig. 2. Hollow grains, on the other hand, appear to be randomly oriented with respect to each other. This "selective grain alignment" could not result from secondary processing.

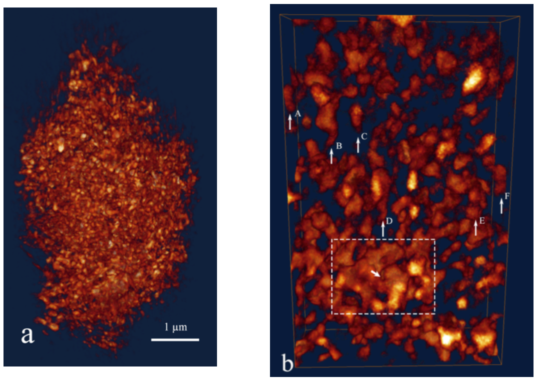

Fig.1. IDP U2015-M-1 containing preferentially oriented elongated grains (e.g., grains A-F in panel b) [from 6]. (a) Volume-rendered image of the entire particle. (b) Volume-rendered image of internal structure with volume 0.9 × 2.3 × 3.7 µm^3. A cluster (dashed rectangle in panel b) contains carbonaceous hollow globules (arrow).

The astrobinary in Fig. 2 (grain E in Fig. 1(b)) is the most pristine and distinct binary identified yet among the aligned elongated composite grains. It is a primordial elementary binary–one formed from axially aligned grain-grain collisions in the cold ISM–and its geometry per se has been preserved, although surface alteration may or may not have occurred since its formation [6]. The astrobinary, overall shaped like a nanodumbbell with a long-to-short axial ratio of ~ 3.3, comprises a pair of nearly equal-sized, oblate, quasi-spheroidal grains connected by the neck (arrow in Fig. 2 (a)) whose intragrain alignment, grain shape and size, porosity, core-mantle structure, and density or compositional gradients meet the astronomical constraints on polarizing interstellar grains [6, 8]. Furthermore, each member of the pair contains a high-density core of twinned octahedral magnetite nanocrystals with flat, faceted surfaces, in contrast to the irregularly shaped "dirty-silicate" mantle exhibiting overall rounded edges and pitted surfaces (Fig. 2) – providing clear evidence that the oriented magnetite nanocrystals were protected from interstellar shocks by the mantle. (Magnetite is a ferrimagnetic mineral that is spontaneously magnetized along its easy axis and strongly magnetic even at room temperature, with octahedral morphology as its characteristic growth habit or shape. Magnetite undergoes a ferroelastic cubic-to-monoclinic phase transition at the Verwey transition temperature T_V of ~120 K, during which the monoclinic twins with orthogonal c-axes (easy axes) are developed.) Each of the magnetite nanocrystals per se must be a single magnetic domain (behaving like a single strong magnetic dipole), given their sizes smaller than the critical size of single-domain magnetite nanoparticles. And they may have stayed below the blocking temperature (above which they become superparamagnetic) during grain growth in the protosolar molecular cloud.

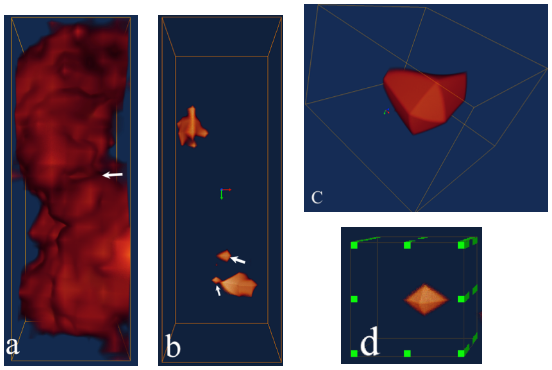

Fig. 2. The astrobinary consists of two axially aligned grains each containing a core of twinned octahedral magnetite nanocrystals [from 6]. (a) and (b) Volume-rendered images showing the astrobinary and the clusters of oriented nanocrystals, respectively. Red, green, and blue arrows in panel (b) denote the X-, Y-, and Z-axes. (c) Close-up of the twinned octahedra (larger arrow in panel (b)) with orthogonal elongated axes (~20 nm long). (d) Close-up of an octahedral nanocrystal (small arrow in panel (b)). The green cube is the voxel size 15.75^3 nm^3 .

The astrobinary and other elongated composite grains became aligned (Fig. 1(b)) in the protoplanetary disk. The grain alignment would not have been expected to occur, however, based on the common assumption that submicron or smaller grains are well coupled to the gas in disks and that Brownian motion governs dust aggregation. Agglomerated grains in this growth scenario should be randomly oriented with respect to one another as sticking grains together by mutual attraction (e.g., van der Waals forces) is realized through random gas–grain collisions. The observed grain alignment implies that the forces or the aligning torques exerted on the elongated composite grains by the local magnetic field were strong enough to overcome the randomizing effects of gas collisions to shape dust growth (regardless of the detailed physics of grain alignment). The grain alignment was locked in place during dust growth, and as a result, forming the elongated particle.

Implications: The observation of the primordial magnetite nanomineral and grain alignments locked in the elongated parent IDP points to an intimate connection between grain alignment and dust evolution in the ISM and disks– providing a potential pathway to rapid dust growth leading to planetesimals in outer protoplanetary disks. Long-range attractive interactions between the opposite poles of magnetic grains increase collision cross sections by orders of magnitude [9-10], which in turn increases collision frequency and dust growth rates. More important, grains with strong magnetic dipoles may readily line up with the ambient magnetic field on a large scale, resulting in rapid growth of larger aggregates with cohesive structures and stronger magnetic dipoles than their individual constituents' thanks to aligned constituent dipoles. (This has been shown in aggregation of small magnetic grains [4], as has in that of larger ~ 0.1 mm charged grains in the presence of an electric field [11-12].) Therefore, the magnetically enhanced dust growth process may be robust and rapid enough to overcome or bypass the barriers and produce centimeter-sized or larger aggregates, leading to planetesimals in the outer regions of protoplanetary disks.

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