TEM AND STXM OBSERVATIONS OF ORGANIC (AND SOME INORGANIC) STARDUST PARTICLES FROM COMET 81P/WILD2. B. T. De Gregorio[1], N. D. Bassim[1], G. D. Cody[2], L. R. Nittler[2], R. M. Stroud[1], and T. J. Zega[1], [1]U.S. Naval Research Laboratory, Code 6366, 4555 Overlook Ave. SW, Washington, DC 20375-5320 (bradley.degregorio@nrl.navy.mil), [2]Carniegie Institution of Washington, Washington, DC.

Introduction: The Stardust mission collected thousands of particles from comet 81P/Wild2 and returned them to Earth. The returned samples include products of interstellar and protostellar processes and relict grains from the early solar nebula, largely unaltered in the low temperature cometary environment. A few Stardust particles contain organic matter, and a portion of this organic matter is clearly interstellar or presolar based on deuterium and ^{15}N isotope excesses over solar values [1]. Characterization of Stardust organics is important for understanding the formation and preservation of interstellar organic matter. Previous studies of Stardust organics reveal a wide range of morphology and composition, with generally greater abundance of N and O heteroatoms than typical meteoritic organic matter [1, 2].

Methods: Electron and X-ray transparent sections of Stardust track particles were embedded in either epoxy or sulfur and prepared by ultramicrotomy at Johnson Space Center or the Naval Research Laboratory. High-resolution transmission electron microscopy (HRTEM), high-angle annular dark-field (HAADF) imaging, electron energy-loss spectroscopy (EELS), and energy-dispersive X-ray spectroscopy (EDS) were performed on a JEOL 2200F field emission transmission electron microscope. Three different synchrotron-based scanning transmission X-ray microscopes (STXM) were used: beamline X1A1 at the National Synchrotron Light Source (NSLS), beamline 5.3.2 at the Advanced Light Source (ALS), and beamline 10ID-1 at the Canadian Light Source (CLS). On each instrument X-ray absorption near-edge structure spectroscopy (XANES) at the carbon absorption edge (and nitrogen and oxygen edges, if possible) was performed.

Results: Ten distinct particles, some with multiple sections, were observed by TEM. Six of these particles have been previously analyzed with XANES [2]. Two of these particles contained only inorganic materials.

Range of morphology. Carbonaceous sections showed a variety of morphologies in TEM images that are not apparent with STXM. Some sections are homogeneous, with high C/Si abundance, and contain carbonyl functional groups (Fig. 1). These particles (such as FC9,13,1,8) appear to contain partial nanoglobules reminiscent of those found in carbonaceous chondrite meteorites [3].

Other sections contain clear organic moieties in XANES and EELS spectra, yet have the appearance of aerogel in TEM images. The organic matter in these sections is distinct from organic contaminants typical for aerogel [2]. Slight variations in aerogel density in TEM images suggest that the cometary organic matter may be incorporated into pores within the aerogel. This may further indicate heating during particle capture was able to volatilize a fraction of the solid organic matter within cometary dust, driving it into the nearby aerogel.

Movement of organics also occurs during epoxy embedding during Stardust sample preparation. Carbonaceous section FC12,16,1,10 is visibly distinct from the surrounding epoxy, yet the XANES spectrum of this section is predominantly epoxy with a lesser proportion of actual cometary organics [2]. These two components appear heterogeneously intermixed in TEM images.

Organics with embedded nanoparticles. Occasionally, small 100-200 nm minerals are observed within organic matter in TEM sections. However, one 5 µm carbonaceous section, C2092,80,43,1, contains abundant nanophase particles, visible as bright spots in HAADF images (Fig. 2). Spot EDS analysis indicates these nanophase particles include Si-, Al-, Fe-, Ti-, and

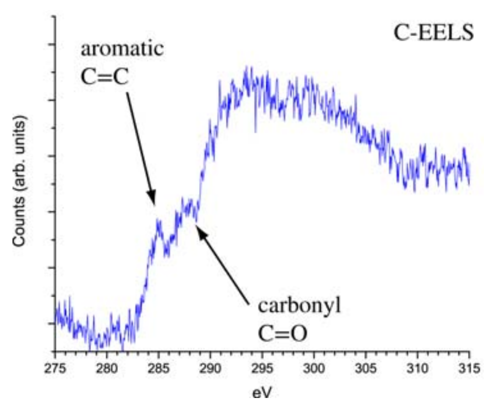

Figure 1. Carbon EELS of section FC9,13,1,8, showing an aromatic carbon peak at 285 eV and a carbonyl peak at 288 eV. The carbonyl peak is likely related to the vinyl ketone peak in previous XANES spectra [2]. The remainder of the edge intensity is due to a continuum of C-C single and double bonds.

Zr-rich phases, occurring mostly as oxides with some sulfides. Most of these nanophases are crystalline in high-resolution images. The carbonaceous component of this section contains abundant nitrogen, and both EELS and XANES spectra for carbon and nitrogen absorption indicates the presence of N-containing organic functional groups (Fig. 3). These include nitrile (286.7 eV for C and 399.8 eV for N), amide (288 eV for C and 401.9 eV for N), and imine (398.8 eV for N).

This particle may be evidence of organic condensation reactions isolated in interstellar or presolar environments rich in cyanide, amino-organics, and formaldehyde. However, it is also possible that this particle is an impact fragment from the Kapton® protective covering of the Stardust spacecraft. Kapton is a N-rich polyimide material, which may be represented by amide absorptions in EELS and XANES spectra.

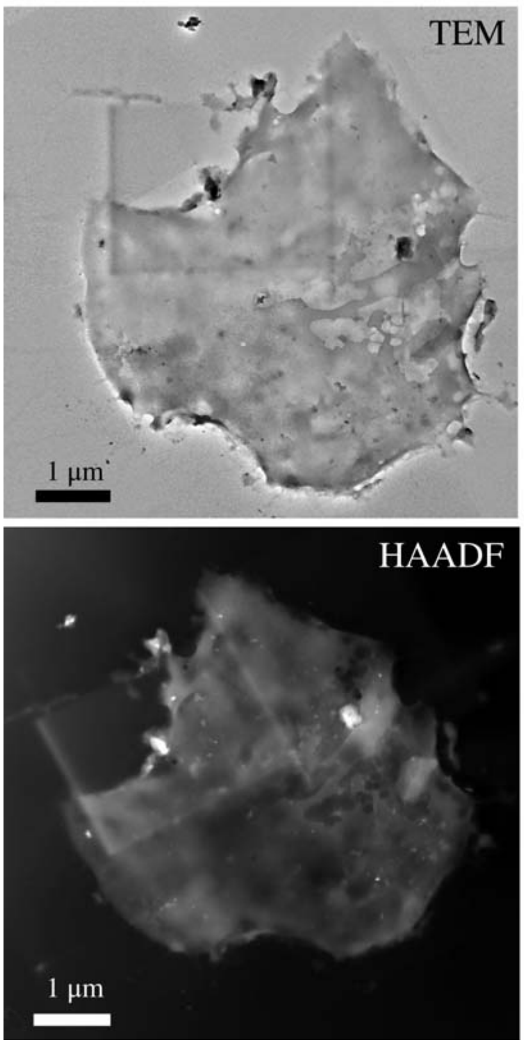

Figure 2. Bright-field TEM and HAADF (Z-contrast) images of section C2092,6,80,43,1. A large rectangular patch of slight beam damage from the ALS x-ray beam is visible in both images.

Inorganic sections. Two Stardust particles contain primarily orthopyroxene surrounded by aerogel. In section C2081,108,20,11,17, the particle is almost pure enstatite ($En_{0.97}$) with minor concentrations of Cr, Ca, and Mn. In sections C2081,108,2,5,16-18, the particle is high-Fe enstatite and appears to contain alternating ortho- and clinoenstatite lamellae. Further work on these sections will reveal the temperature history of the cometary particles, and the probable cosmic environments in which they might have condensed.

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References: [1] Sandford, S. A., *et al.* (2006) *Science, 314*, 1720-1724. [2] Cody, G. D., *et al.* (*in press*) *Meteoritics & Planet. Sci.* [3] Garvie, L. A. J. (2006) *Carbon, 44,* 158-160.

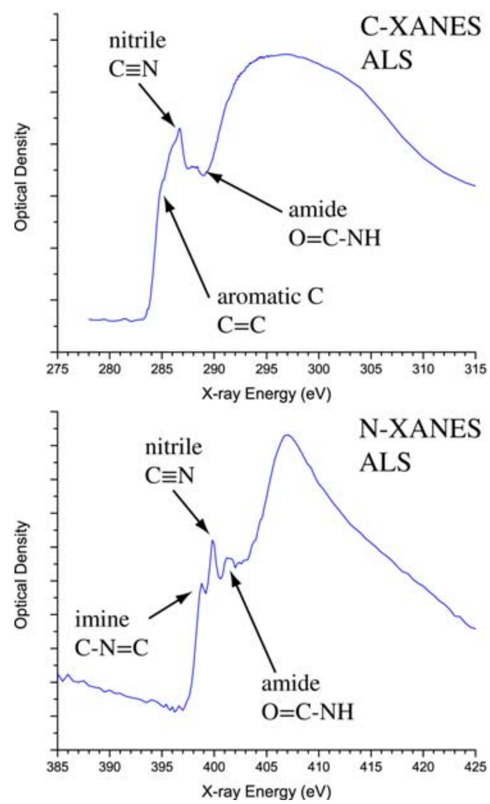

Figure 3. Carbon and nitrogen XANES from section C2092,6,80,43,1 (collected at ALS). Several distinct N-containing functional groups are present and consistent between the two spectra. Aromatic carbon is indicated by a peak "shoulder" at 285 eV.