BULK MINERALOGY AND THREE DIMENSIONAL TOMOGRAPHY OF INDIVIDUAL STARDUST PARTICLES. T. Nakamura[1], A. Tsuchiyama[2], T. Akaki[1], K. Uesugi[3], T. Nakano[4] and T. Noguchi[5], [1] Department of Earth and Planetary Science, Faculty of Science, Kyushu University, Hakozaki, Fukuoka 812-8581, Japan (tomoki@geo.kyushu-u.ac.jp), [2] Department of Earth and Space Science, Graduate School of Science, Osaka University, Toyonaka 560-0043, Japan, [3]Japan Synchrotron Radiation Research Institute, SPring-8, Sayo, Hyogo 679-5198, Japan, [4]Geological Survey of Japan, Advanced Industrial Science and Technology, Tsukuba 305-8567, Japan, [5]Department of Materials and Biological Sciences, Ibaraki University, 2-1-1 Bunkyo, Mito 310-8512, Japan

Introduction: Many cometary particles were recovered by the Stardust mission. They are very small and most of them have diameter less than 10 microns. Therefore, characterization of these small particles requires most-advanced analytical techniques. We have utilized synchrotron radiation X-ray to characterize bulk mineralogy and three dimensional structures of individual stardust particles.

Experimental procedures: Individual particles were first analyzed by synchrotron X-ray diffraction (SXRD). Each particle was mounted on a thin glass fiber of 3-micron thickness using a small amount acetone-soluble bond and placed in the Gandolfi camera for exposure to synchrotron X-rays with a wavelength of 2.161 ± 0.001 Å for 3 hours to produce a powder X-ray diffraction pattern. The analyses were performed at beam line 3A of the Photon Factory Institute of Material Science, High Energy Accelerator Research Organization and beam line 37XU of Japan Synchrotron Radiation Research Institute (SPring-8); for details of these procedures see [1].

Following SXRD analyses, four particles with different SXRD characteristics were selected. They were imaged and analyzed analyzed by micro-tomography at beam line BL437XU of SPring-8. The imaging experiments were made using imaging tomography [2] at 8 keV with 3600 projections for each slice. Three-dimensional structures were obtained from 490 slice images with a voxel (pixel in 3-D) size of 42.5x42.5x42.5 nm. The solid portion (whole grain) and the highly absorbed portion that might correspond to Fe-Si or Fe-Ni-S phases were obtained by thresholding the CT-image contrast; details for the procedures see [1].

Results and discussion: We analyzed 28 particles, among which 25 particles were taken from track 35 and 3 particles from track 44. Track 35 is 11.7 mm length with a large bulboid space in front and a long, straight main track with a terminal particle at base. Several subtracks with terminal particles are also present. Among 25 particles analyzed, 23 were picked up from the wall of the bulb and 2 from terminal particles. On the other hand, the track 44 is much larger (~ 0.8 cm) than the track 35, but it is still in the aerogel tray, so precise size of the track is unknown. Three particles were pulled from the wall of the track.

The results of SXRD showed that stardust particles can be classified to only two types: crystalline type and amorphous-rich type. The crystalline type shows very sharp diffractions of silicates and Fe metal, whereas amorphous-rich type shows very broad reflections of Fe metal and sulfide with or without minor amounts of silicates. Among 28 particles investigated, only three are classified to crystalline type and the rest is amorphous-rich type. Two particles of crystalline type and two particles of amorphous-rich type are also analyzed by micro-tomography. The results indicate that crystalline-type particles consist mostly of relatively coarse (more than 1 micron diameter) silicate crystals such as olivine and low-Ca pyroxene and the crystals contact each other without any pore spaces. On the other hand, the amorphous-rich type is porous aggregates showing network structure with numerous voids. Two representative particles, one from crystalline type and the other from amorphous-rich type, are described below for detail mineralogy and three dimensional structures.

Crystalline type: Fig. 1a-c show SXRD and high-resolution tomography of stardust particle C2054, 0, 35, 6 with approximately 15 microns in size. It consists of Mg-rich olivine, low-Ca pyroxene and kamacite (Fig. 1a). All reflections are very sharp, indicating that the particle is well crystalline. Tomography shows that it is a non-porous particle (Figs. 1b and c). All minerals are coarse and several microns in size. The internal texture is poikilitic: subhedral olivine crystals occur within anhedral pyroxene. The texture suggests that the particle was crystallized from a melt: olivine crystallized first followed by pyroxene at around 1550 ^{o}C.

The crystalline-type particles are not melt product during capture into the aerogel, because no mixing with melted silica aerogel is observed. Therefore, these particles are relict of indigenous material of comet Wild II. The presence of plagioclase in C2054,

0, 35, 4, which requires slow cooling for crystallization, supports this interpretation. These crystalline particles formed via high-temperature episodes that predate formation of comet Wild II. This finding, together with CAI materials in other tracks [3], indicates that Wild II contains high-temperature materials that are difficult to produce at regions of Kuiper belt.

Amorphous-rich type: C2004, 1, 44, 3, 0 is irregularly shaped and is 15 x 20 μm in size (Fig. 2a). Micro-tomography shows a porous material with numerous voids that are mostly <1 μm in size, a few large voids (3-4 μm) and a three-dimensional network of fine-grained materials probably made of melted aerogel, silicates, sulfides and suessite (Fig. 2a-c). The presence of abundant voids (~56 vol. % porosity) might support melting, devolatilization and rapid cooling. The surface is irregular (Fig. 2d).

The SXRD analysis shows only broad and no sharp reflections (Fig. 2e). The diffraction maxima are identified as suessite, Fe_3Si, and sulfide. Sulfide is either troilite (FeS) or pyrrhotite ($Fe_{1-x}S$) but this identification is not conclusive because the sulfide diffraction peaks are too broad to distinguish the two minerals that give strongest lines at diffraction angles close to each other. We can distinguish suessite from kamacite on the basis of the diffraction angles (Fig. 2e). Suessite consistently yields diffraction peaks at angles higher than kamacite, since the suessite unit cell is smaller than kamacite by approximately 1% due to substitution of Fe by the smaller Si atom. The diffraction peaks for this particle are almost identical to those of suessite (Fig. 2e).

The mode of suessite and sulfide phases is approximately 0.06 vol.% based on the 3-D tomography images (Fig.2d). The maximum size of these individual phases is about 700 nm and most are <300 nm. Suessite along with hapkeite Fe_2Si and more Fe-rich iron-silicides up to Fe_7Si_2 were found to form near the entrance of aerogel track #44 [4]. These iron-silicides were probably formed during capture melting from metallic Si, reduced product of SiO_2 in aerogel, and metallic Fe, indigenous Wild II material.

References: [1] Nakamura T. et al. (2007) *Meteoritics & Planet. Sci.*, submitted. [2] Uesugi K. et al. (2006) *Proc. SPIE, 6318*, in press. [3] Brownlee D. et al. (2006) *Science, 314*, 1711. [4] Rietmeijer et al. (2007) *Meteoritics & Planet. Sci.*, submitted.

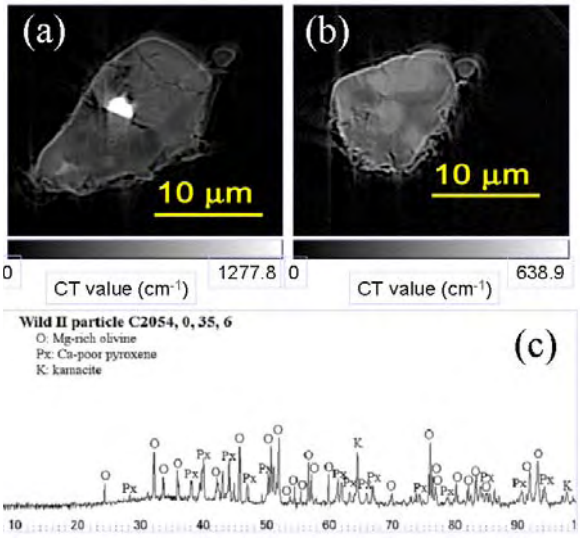

Fig. 1. Stardust particle C2054, 0, 35, 6. (a-b) Micro-tomography image shows it consists of olivine (light grey), pyroxene (dark grey), and kamacite (white). (c) SXRD pattern.

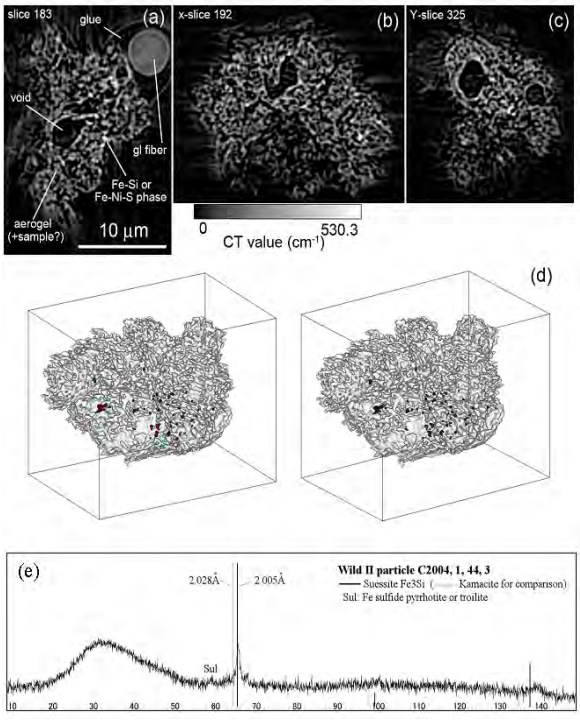

Fig. 2. Stardust particle C2004,1,44,3,0. (a-c) Micro-tomography image of a cross-section showing the many voids in this grain and the network of light-colored material. Scale bars and gray scale are identical in all three the images. (d) A stereographic images of the external shape of the sample. (e) SXRD pattern.