Three-dimensional Structures of Cosmic Dust by Microtomography

X-ray computed tomography (CT) is a nondestructive technique for obtaining the internal structures of objects using the X-ray absorption of the materials. Three-dimensional structures can be obtained by constructing a number of successive CT images. Uesugi *et al*. [1] have developed an SR-based projection microtomography system named SP-μCT. A calculated value of the linear attenuation coefficient (LAC), which is called a CT value, is stored in each pixel of a CT image. The relationship between the CT and LAC values obtained for SP-μCT [2] enables the quantitative estimation of materials using their CT values and elemental mapping using the absorption edges of elements [3].

Extraterrestrial materials of < 1 mm in size are called cosmic dust, in contrast to meteorites (> 1 mm). They are classified into cosmic spherules, micrometeorites (MMs) and interplanetary dust particles (IDPs). Cosmic spherules are objects made spherical by melting due to heating during their entry into the Earth's atmosphere; they are collected from snow and ice in the polar region and from mud on oceanic floors. MMs are irregularly shaped particles of a few tens to a few hundreds μm in size and collected from snow and ice in the polar region. Most of them are more or less suffered from heating during atmospheric entry. IDPs are particles of about 10 μm in size and are collected in the stratosphere. They are not affected by any heating due to their small size. Cosmic dust originates from primitive materials of the solar system, which are similar to primitive meteorites, named carbonaceous chondrites. However, they probably have a wider variety of origins than meteorites (cosmic dust might come from asteroids and comets while carbonaceous chondrites come from asteroids). Accordingly, it is expected that specific information that cannot be obtained from meteorites alone can be extracted from cosmic dust. As cosmic dust is small, research has usually been done using scanning and transmission electron microscopes. We have applied microtomography to cosmic dust for the first time.

Cosmic spherules (50-300 μm) collected from Antarctica by the National Institute of Polar Research (NIPR) were imaged by SP-μCT at beamlines **BL20XU** and **BL47XU** with the pixel size of 0.5 μm [4]. Their three-dimensional external shapes were extracted from CT images (Fig. 1) and approximated as three-dimensional ellipsoids with the axial diameters of A, B and C ($A \geq B \geq C$). The axial ratios are plotted together with the data for another type of extraterrestrial spherical object characteristically included in primitive meteorites, chondrules, whose data have already been obtained by SP-μCT (Fig. 2). The shapes of cosmic spherules are recognized as belonging to three groups. For group (1), the aspect ratios ($p = C/A$) are larger than 0.8 and many of them are oblate ($B/A < C/B$ or $\log n > 0$: $(C/B)=(B/A)n$); group (2), $0.6 < p < 0.8$ and they are prolate ($B/A > C/B$ or $\log n < 0$); and group (3), are dumbbell shaped ($p \sim 0.3$-0.4). Groups (1) and (2) were also recognized in chondrules. These shapes can be explained by a high-speed rotation of the spherical objects: flattening of molten droplets during melting (oblate), deformation by shape instability (prolate), and further deformation (dumbbell shaped). As the cosmic spherules were formed by shock wave heating during their atmospheric entry, the common shape features might indicate that chondrules were also formed by shock wave melting in the primordial solar nebula. The rotation rates estimated from the oblate cosmic spherules are >1000 rps (50-300 rps for chondrules). Such extremely high rotation rates might be related to cometary dust, which

(a) (b) (c)

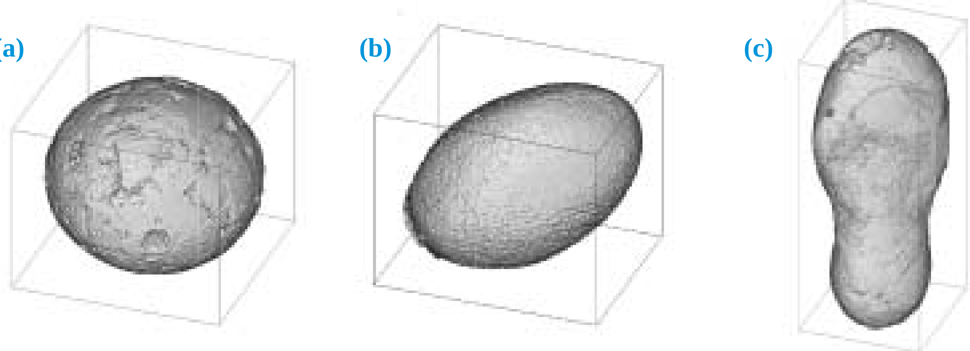

Fig. 1. Bird's-eye-views of cosmic spherules. **(a)** Oblate spherule (133 × 162 × 164 μm^3). **(b)** Prolate spherule (80 × 88 × 124 μm^3). **(c)** Dumbbell shaped spherule (88 × 114 × 314 μm^3).

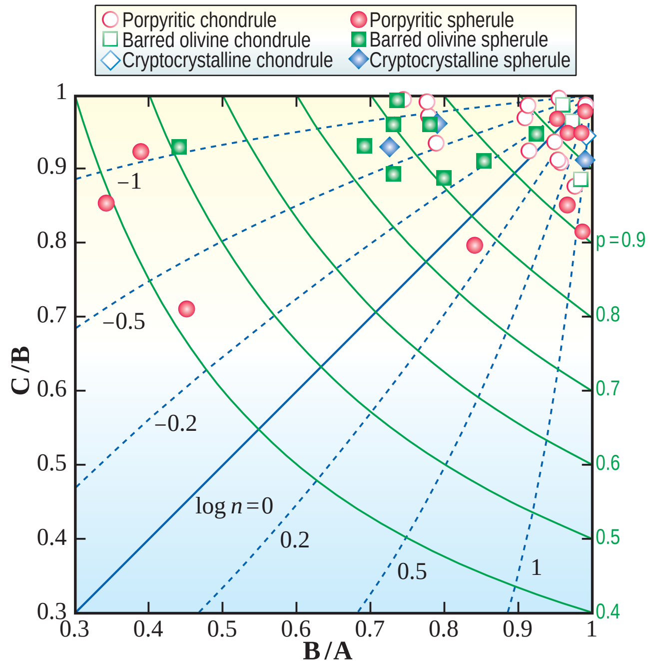

Fig. 2. Diagram showing external shapes of cosmic spherules (solid symbols) and chondrules (open symbols). Cosmic spherule and chondrule textures are also shown.

enters into the atmosphere much faster than asteroidal dust.

MMs (70-320 µm) collected from Antarctica by NIPR were also imaged by SP-µCT at BL20XU and BL47XU with the pixel size of 0.5 µm [5]. If an MM is heated during entry into the atmosphere, hydrous silicates, which were originally present in the MM, are dehydrated and become porous (scoriaceous MM: Fig. 3), while non-scoriaceous MMs suffer from slight heating. Solid portions (e.g., the white portion in Fig. 3(b)) were extracted three-dimensionally by binarization from CT images. We can also recognize voids included in the solid portions (e.g., the green portions in Fig. 3(b)). The porosities of scoriaceous and non-scoriaceous MMs are 5-28% and < 6%, respectively.

As the size of the voxel (pixel in 3D) is known in the CT images, bulk and solid volumes with and without internal voids, respectively, were obtained by counting the number of voxels belonging to the objects. The masses of the samples were also measured using an ultra-microbalance, which can measure masses of > 0.1 µg (> 50-100 µm), and their densities were calculated. The bulk and solid densities were 2.0±0.4 and 2.1±0.4 g/cm^3 for the non-scoriaceous MMs and 2.2±0.1 and 2.6±0.3 g/cm^3 for the scoriaceous MMs, respectively. The bulk densities are almost identical irrespective of vesiculation. Discrepancy between the solid density of a non-heated MM (1.8 g/cm^3) and the grain density (~2.6 g/cm^3) roughly estimated from their constituent mineral phases and their modes strongly suggests that numerous submicron pores smaller than the spatial resolution of the CT images are present. This might explain the observed low densities of asteroids.

We are now applying this technique to IDPs to obtain their fractal dimensions and enable 3D Fe mapping. This technique is also useful for small samples, which will be retrieved from an asteroid (Hayabusa mission by JAXA) and a comet (Stardust mission by NASA) by spacecrafts in the near future.

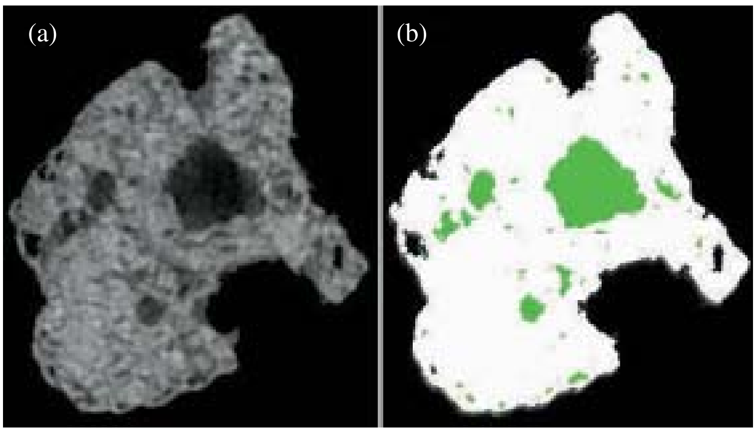

Fig. 3. Antarctic micrometeorites. **(a)** CT image. **(b)** Solid portions extracted by binarization. The width of each image is 75 µm.

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