Three-dimensional Structures of Chondrules: their Motions in the Primordial Solar Nebula

Chondrules are characteristic constituents in primitive meteorites, or chondrites. These tiny spherical objects (0.1 to a few mm in diameter) are mainly composed of silicates with minor amounts of metallic iron and/or iron sulfide. Chondrules were formed in the primordial solar nebula about 4.5 billion years ago prior to the formation of the Earth. They were once molten due to the instantaneous heating of solid precursors and cooled rapidly. In order to elucidate their origin and obtain information on the solar nebula, many researchers have examined chondrules extensively using different methods. However, their three-dimensional structures have not been thoroughly investigated so far. X-ray computed tomography (CT) can give information about the internal structure without damaging the samples and provide 3-D structures by stacking successive sliced images. In SPring-8, a micro X-ray CT system has been developed (Fig. 1) [1-2]. The major advantages of an X-ray CT system using SR are (i) high resolution 3-D images due to the well-collimated beam and (ii) elimination of CT image artifacts (beam hardening) and qualitative correlation of CT image brightness (CT-value) with linear attenuation coefficient by using a monochromatic beam. We applied this system to the chondrules.

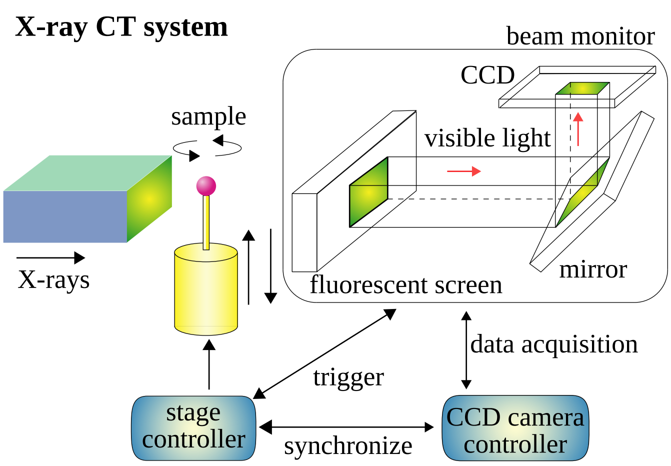

Fig. 1. A schematic illustration of micro X-ray CT system at BL20B2.

Chondrules of about 1-2 mm in diameter taken from the Allende meteorite (CV3 chondrite) were imaged at beamline **BL20B2** with monochromatic beams at 17.5 - 25 keV [3]. The cross sectional images (CT images) were reconstructed from 360 projections taken by sample rotation. The 3-D structures were obtained from 150-300 images. The voxel size of 5.83 µm × 5.83 µm × 5.83 µm ("voxel" is an element of 3-D images whereas the term "pixel" is used in 2-D images) gave a spatial resolution of about 13 µm [1]. Figure 2 shows examples of 3-D CT images of the chondrules. We examined both the external shapes and internal structures of the chondrules three-dimensionally using image analysis techniques.

It is known that the chondrules are not perfect spheres. This was discovered by the two-dimensional observation of thin sections. However, their external 3-D shapes have not been described qualitatively. We approximated the shapes of the chondrules as ellipsoids with three different axial radii (a, b and c) [4]. We found that the shapes of the chondrules are diverse from oblate shapes ($a < b \sim c$), general ellipsoids ($a < b < c$) to prolate shapes ($a \sim b < c$) with the aspect ratio of 0.73 - 0.97 (Fig. 3).

Chondrules contain voids as well as metal and sulfide grains. It is hard to recognize voids in thin sections by conventional means because some parts of the samples might be removed when making thin sections. The CT study showed that most of the chondrules have voids (<0.001 - 0.9 vol.%). This shows that voids are an important constituent. Voids in the chondrules may be formed by

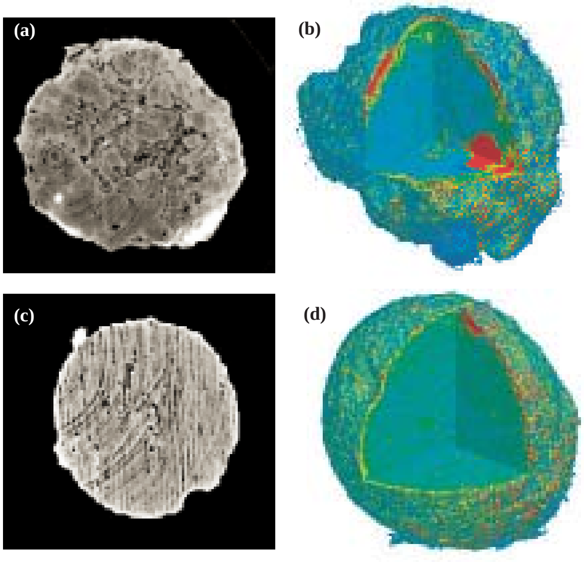

Fig. 2. Examples of CT images of chondrules and their 3-D structures. ***(a)*** *A CT image of porphyritic chondrule.* ***(b)*** *Its 3-D structure.* ***(c)*** *A CT image of barred olivine chondrule.* ***(d)*** *Its 3-D structure. 3-D images are rendered in pseudo color.*

(i) bubbling of volatile components, (ii) trapping of nebula gas during chondrule formation by instantaneous heating of dust balls or (iii) shrinking of chondrules by solidification. We found that the voids are concentrated along the minor axis of an oblate chondrule [5]. This strongly suggests that the chondrule was spinning during their formation in a molten state and the voids were moved towards the minor axis by centrifugal force. The 3-D distribution of metal and sulfide grains also shows spinning along the minor axes of the oblate chondrules or along the major axes of the prolate ones [4].

Chondrules have different textures, such as porphyritic and barred olivine (BO). In BO chondrules, parallel sets of bar-shaped crystals of olivine ($(Mg,Fe)_2SiO_4$) were observed in thin sections. The CT study showed that BO chondrules consist of parallel sets of thin olivine plates [3]. Interestingly, these BO chondrules are oblate and the normal directions of the olivine plates are almost the same as the minor axes of the oblate chondrules (Fig. 4). If we assume that all BO chondrules are oblate or prolate, we can estimate their 3-D structures from the thin sections two-dimensionally. Statistical observation of BO chondrules in thin sections suggested that the normal directions are nearly parallel to the minor axes of many oblate chondrules or to the major axes of some prolate chondrules. These features may be also explained by the spinning of the chondrules probably because centrifugal force affects the nucleation and crystallization of olivine although no definitive mechanism is known at present.

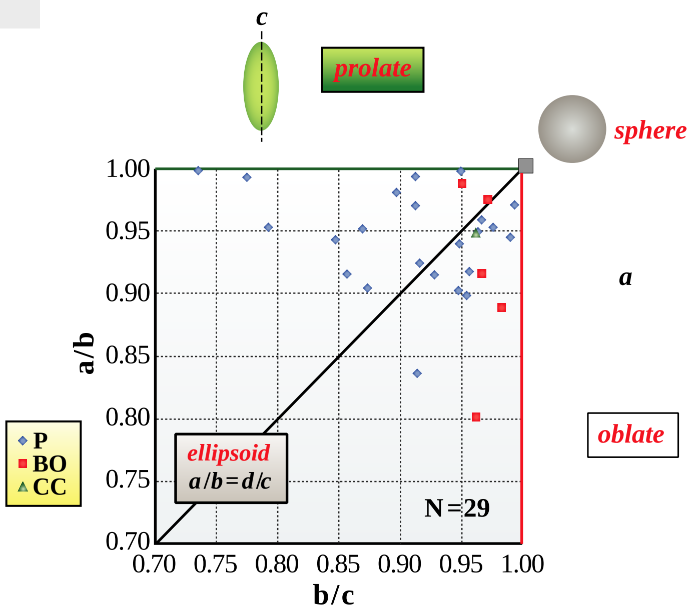

Fig. 3. Aspect ratios, a/b and b/c, of chondrules. The axial radii, a, b and c, were obtained by ellipsoid fitting for each chondrules. P: porphyritic, BO: barred olivine, CC: crypto crystalline.

The idea of spinning chondrules leads to important information on chondrule formation and nebula conditions. Prolate chondrules might be formed by aerodynamic drag during molten states. The major axis should correspond to the rotation axis and the parallel axis to the direction of movement, like a volcanic bomb or a flying football. If this is the case, the presence of prolate chondrules shows that some dense gas was present in the nebula where the chondrules were formed, or that the relation between the gas pressure and the relative speed of chondrule motion can be estimated from the aspect ratios of the prolate chondrules. On the other hand, we can estimate the spinning rates of the oblate chondrules by considering the balance between the surface tension of droplet chondrules and centrifugal forces by the spinning. The angular velocity of rotation, the equatorial radius of the drop, its density and the interfacial surface tension determines the shape of such rotating droplet. The spinning rate of the chondrules is estimated to be about 50 - 200 rps. Such a high spinning rate favors a specific chondrule formation process, such as rotation by drag heating of irregular-shaped dust balls by a shock wave or collision of small heavenly bodies.

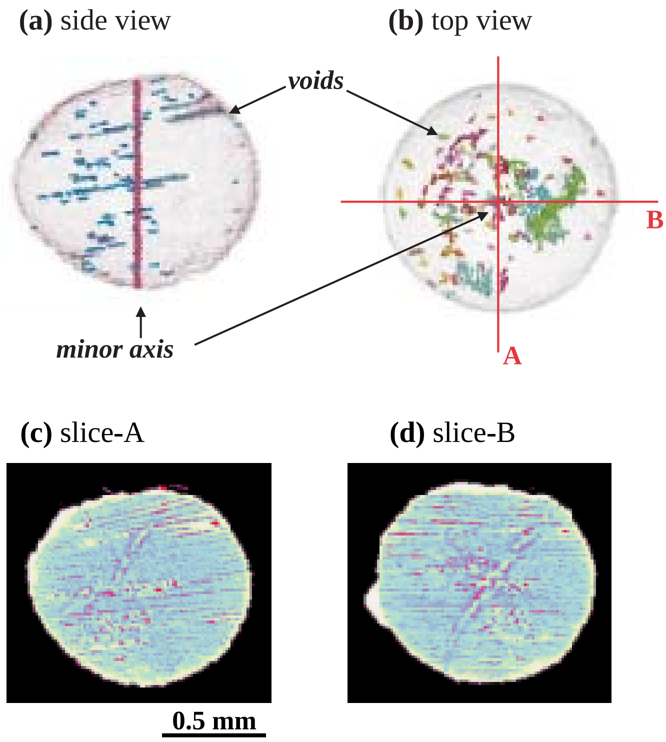

*Fig. 4. 3-D structure of a barred olivine chondrule. Rendered in pseudo color. **(a)** A side view of the oblate chodrule. **(b)** A top view of the oblate chodrule. **(c)** A sliced image along A-direction. **(d)** A sliced image along B-direction. Individual voids are shown as different colors in **(a)** and **(b)**. A parallel set of olivine bars (cyan) is seen in **(c)** and **(d)**.*

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