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3-D shapes and internal structures of chondrules by X-ray CT method - their high-speed rotation and movement in nebular gas

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Chondrules are one of the major constituents of primitive meteorites, chondrites. They have been examined to understand their formation process and discuss the evolution of the primordial solar nebula. Especially, chemical analyses of isotopes and minor elements have been carried out extensively due to recent development of analytical apparatus and give much information, such as their formation ages. On the other hand, progress in physical aspects has not been made much.

It is accepted from their spherical shapes that chondrules were once molten under micro-gravity and cooled. However, they are not strictly spheres. Recent research on 3-D structures of chondrules using high-resolution X-ray CT method shows that there is an oblate chondrule [1]. 3-D distribution of voids in the chondrule indicates that it was spinning during melting. However, such conclusion should be verified by a statistical study.

In the present study, we imaged chondrules removed from the Allende meteorite (CV3) using high-resolution X-ray CT system equipped at synchrotron radiation facility, SPring-8 [2]. The external shapes and distribution of metal/sulfide grains and voids inside of about 20 chondrules with smooth surfaces were analyzed. As a result, we found prolate chondrules (aspect ratio 0.74-0.98) and non-equiaxial chondrules as well as oblate ones (aspect ratio 0.88-0.98). The moments of inertia of metal/sulfide grains or voids around the symmetrical rotation axes of the oblate and prolate chondrules were obtained. The comparison with those of random distribution shows that metal/sulfide grains tend to be present apart from the axis, while voids near the axis. These results can be explained by rotation of the chondrules during melting: heavy metal/sulfide grains and light voids move apart from or towards the rotation axis.

We can estimate high rotation rates of about 50-300 rounds/sec for the oblate chondrules by assuming that these flat shapes were equilibrium shapes, where centrifugal force was balanced with surface tension of chondrule melts [3]. On the other hand, the prolate shapes were formed by elongation along the long axis due to gas drag during movement in a nebular gas and rotation around the long axis. A 3-D model of plaster, which was formed from the CT images of a prolate chondrule, shows the shape is asymmetric with respect to the long axis. The moving direction of the chondrule can be estimated from the asymmetric shape. The prolate shapes strongly suggest the presence of a gas in a chondrule formation region. This is qualitatively consistent with cooling rates estimated by reproduction experiments of chondrules [4]. If we know the rotation rate, the products of gas pressure and moving rate can be estimated from the prolate shapes.

The high-speed rotation during chondrule formation largely constrains their formation process. It may be possible to make high-speed rotation by the shock wave model. However, the shock wave model might not form prolate chondrules, where the moving direction should be parallel to the rotation axis. In the oblate chondrules, negative correlation between the aspect ratio and the size is present. This indicates that the angular velocities of chondrules did not vary largely.

The most of the chondrules imaged in this study have voids. This shows that voids are important constituents ofn chondrules as well as silicates and metal/sulfides although their amounts are small (less than 3 vol.%). The 3-D distribution of voids in an oblate barred olivine chondrule suggests that the voids were formed by bubbling due to increase of the concentration of volatile components in a melt after olivine crystallization.

[1] Tsuchiyama et al. (2000) LPSC, XXXI,1566. [2] Uesugi et al. (1999) Proc. SPIE, 3772, 214. [3] Chandrasekhar (1965) Proc. Roy. Soc. London, A, 286, 1. [4] Tsuchiyama et al. (1980) EPSL, 48, 155.