SHOCK-WAVE HEATING MODEL FOR CHONDRULE FORMATION: HYDRODYNAMICS OF ROTATING DROPLETS EXPOSED TO HIGH-VELOCITY GAS FLOWS. H. Miura[1,2] and T. Nakamoto[3], [1]Pure and Applied Sciences, University of Tsukuba, Japan (miurah@ccs.tsukuba.ac.jp), [2]Research Fellow of the Japan Society for the Promotion of Science, [3]Center for Computational Sciences, University of Tsukuba, Japan.

Introduction: The data of chondrule shapes is a strong clue for elucidating the chondrule formation mechanism. Recently, the three-dimensional data of chondrule shapes has been measured by the X-ray microtomography [1]. The external shapes were approximated as three-axial ellipsoids with a-, b-, and c-axes (axial radii are A, B, and C (A≥B≥C), respectively). The plot of C/B vs. B/A shows that two groups can be recognized: oblate to prolate chondrules with large C/B and B/A of 0.9-1.0 (group-A) and prolate chondrules with relatively small B/A of 0.74-0.78 (group-B). The oblate chondrules are naturally explained by the rapid rotation of molten droplets [1, 2]. However, the origin of the prolate shapes is not clear.

On the other hand, in the shock-wave heating model, which is one of the most plausible models for chondrule formation [e.g., 3], it is naturally expected that the molten droplet is exposed to the high-velocity rarefied gas flow. The magnitude of the deformation of the molten droplet has been analytically investigated [4]. Although the analysis by [4] did not consider the effect of the rotation, the rotation would play an important role in the droplet deformation. It is thought that the droplet deformation would affect the shapes of chondrules formed after re-solidification.

In this study, we perform hydrodynamic simulations of molten silicate dust particles in the framework of the shock-wave heating. We numerically solve the hydrodynamical equations of rapidly rotating molten droplets exposed to the high-velocity rarefied gas and investigate the hydrodynamics of the droplet.

Model: In the shock-wave heating model, the rotation of the precursor dust particle is naturally expected if the dust shape is irregular. Before the dust particles melt, it is thought that the precursor dust particles are not perfect spheres and have many bumps on its surface. The asymmetrical structures would cause the net torque in the gas flow and the precursor dust particles should begin to rotate. Therefore, it is expected that the dust particle has already obtained some angular velocity when it melts.

We can roughly estimate the angular velocity Ω of the precursor dust particle and use it as the initial angular velocity of the molten droplet. We numerically solve the hydrodynamical equations using the CIP method [e.g., 5]. The ram pressure of the gas flow is fixed at 4000 dyne cm^{-2}, which is the typical value of the high-density shock waves (pre-shock gas number density is ~10^{14} cm^{-3} and the shock velocity is ~10 km s^{-1}). The viscous coefficient of 1.3 poises and the surface tension of 400 dyne cm^{-1} are the typical value of well-molten silicate dust particles. Finally, we show the results for the droplet radius of 500 μm in this paper.

Numerical Results: We show a example of the hydrodynamic simulations in Fig. 1, which is the *xy*-section of the molten droplet about 2.1 msec later since the initial state. The gas flows from left to right in the figure (*x*-direction). The initial angular velocity is set to be Ω = 971 s^{-1} and the rotation axis is the *z*-axis. Even if the time passes more, the external shape of the droplet does not change significantly. In Fig. 1, we found that the droplet elongates toward the *y*-direction comparing with the *x*-direction. Moreover, the *z*-axis of the droplet, which does not appear in Fig. 1, is shorter than the *y*-axis because of the centrifugal force, which extends the droplet shape toward *x*- and *y*-directions (rotation axis is *z*-axis). As a result, the droplet becomes a prolate shape, which has a major axis longer than other two shorter axes.

We calculate for the cases with different angular velocities in a range from Ω = 560 to 1253 s^{-1}. In each case, we obtain the quasi-steady shape of the droplet after a certain time passes. The axial ratios of the quasi-steady shapes depend on the initial angular velocity. The numerical simulations show that if the angular velocity is small, the droplet is the oblate shape. On the contrary, the droplet shape changes from the oblate to prolate as the angular velocity increases.

Analytic Expression: In order to understand the reason why the droplet shape changes from oblate to prolate as the angular velocity increases, we derive the analytic expression of the three-dimensional droplet shape taking into account the both effects; the gas drag force and the rotation. Our derivations are based on following two analytic formalisms; the deformation of the droplet exposed to the rarefied gas flow without the rotation [4] and the equilibrium shape of rotating droplet without the effect of the gas flow [2]. We can know how the droplet deforms from a perfect sphere due to these two effects separately. We assume that the external shape of rotating droplet exposed to the gas flow can be expressed by a simple superposition of above two formalisms. Fig. 2 shows the radius of the droplet for each direction (*x*-, *y*-, and *z*-axes) as a function of the angular velocity Ω, which is proportional to the square root of the non-dimensional parameter *f*. In this case, $f = 0.1$ corresponds to $\Omega = 560\ s^{-1}$ (the correspondence depends on the ram pressure of the gas flow and the droplet radius). When $f = 0$ ($\Omega = 0$), which means no rotation, *y*- and *z*-axes are the same and the *x*-axis is shorter than them due to the gas drag force. It is the oblate shape. If the droplet begins to rotate, the *x*- and *y*-axes get longer by the centrifugal force (rotation axis is *z*-axis). In contrast, the droplet shrinks in the *z*-direction. Finally, the *x*- and *z*-axes become the same length at $f = 0.348$ ($\Omega = 1046\ s^{-1}$). It is the prolate shape.

We compare our numerical results and the analytic expression on the plot of C/B vs. B/A (Fig. 3). The solid curve is the analytic expression and the numbers beside the solid curve indicate the value of *f*. The color filled circles are the simulation results; red for $f = 0.1$ ($\Omega = 560\ s^{-1}$), green for $f = 0.3$ ($\Omega = 971\ s^{-1}$), and blue for $f = 0.5$ ($\Omega = 1253\ s^{-1}$). The deeper colors indicate the later stage of the time evolutions. We can found that the numerical simulations well match with the analytic expression. However, if the angular velocity exceeds about 1000 s^{-1}, the external shape is apart from the analytic expression and to be more largely deformed prolate shape.

Conclusions: We performed the hydrodynamical simulations of rotating molten silicate dust particles exposed to the gas flow. We considered that the dust particles gain the angular momentum from the ambient gas flow before they melt and the rotation axis is perpendicular to the direction of the gas flow. It is found that the molten droplets take various shapes, not only the oblate shape, but also the prolate shape. We also derived the analytic expression of the droplet shape and it showed a good agreement with the numerical simulations if the angular velocity of the droplet is not so large. We are planning to investigate the high-viscous fluid dynamics in the same situation because it is thought that the droplet shapes just before re-solidification would strongly affect the final shapes of chondrules.

References: [1] Tsuchiyama A., et al. (2003) *LPS XXXIV*, 1271-1272. [2] Chandrasekhar S., (1964) *Proc. Roy. Soc. London, A., 286*, 1-26. [3] Iida A., et al. (2001) *Icarus, 153*, 430-450. [4] Sekiya M., et al., (2003) *Prog. Theo. Phys., 109*, 717-728. [5] Yabe T., et al., (2001) *J. Comp. Phys., 169*, 556-593.

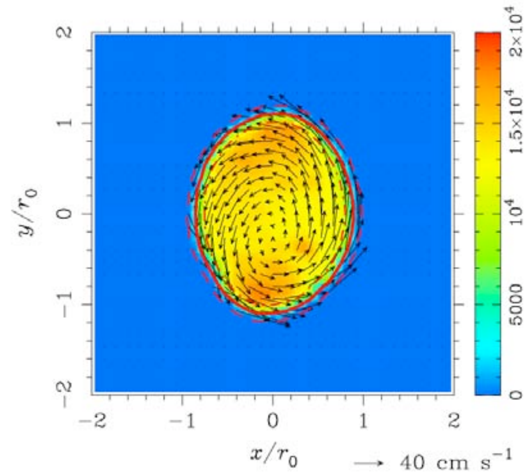

Fig. 1: Snap shot of the droplet at the xy-section. The color contour is the hydrostatic pressure, vectors are the velocity field, and the red solid curve indicates the interface between the droplet and the ambient gas.

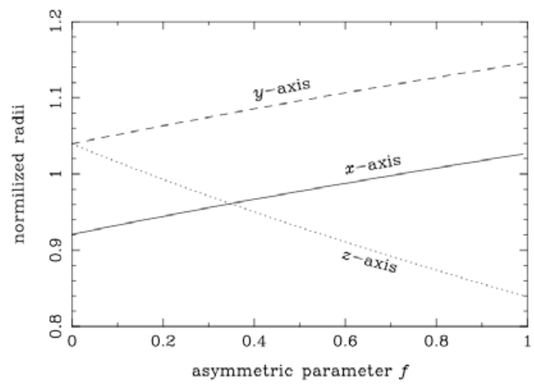

Fig.2: Length of each axis of the droplet as a function of the rotation rate.

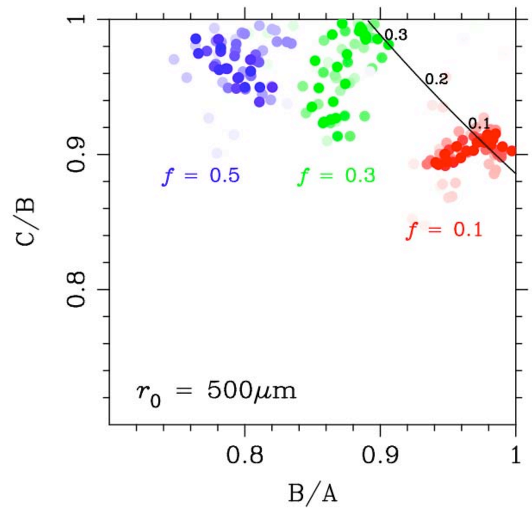

Fig. 3: The simulation results (filled circles) and the analytic expression of the droplet shape (solid curve).