SHOCK-WAVE HEATING MODEL FOR CHONDRULE FORMATION: ORIGIN OF CHONDRULE SHAPES. H. Miura[1,2], T. Nakamoto[3], and D. Masao[4], [1]Theoretical Astrophysics Group, Department of Physics, Kyoto University, Japan (miurah@tap.scphys.kyoto-u.ac.jp), [2]Research Fellow of the Japan Society for the Promotion of Science, [3]Earth and Planetary Science, Tokyo Institute of Technology, Japan (nakamoto@geo.titech.ac.jp), [4]Pure and Applied Sciences, University of Tsukuba, Japan (doi@het.ph.tsukuba.ac.jp).

Introduction: The data of chondrule shapes is a strong clue for elucidating the chondrule formation mechanism. 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 ($\mathrm{A} \geq \mathrm{B} \geq \mathrm{C}$), respectively). The plot of C/B vs. B/A shows that two groups can be recognized: oblate to prolate chondrules with C/B and B/A close to unity (group-A) and prolate chondrules with relatively small B/A of 0.74-0.78 (group-B). The oblate chondrules might be naturally explained by the rapid rotation of molten droplets [1]. However, the origin of the prolate shapes is not clear.

In the shock-wave heating model, which is one of the most plausible models for chondrule formation [e.g., 2], it is naturally expected that the molten precursor dust particle (droplet) is exposed to the high-velocity gas flow. The strong gas ram pressure causes hydrodynamics of the droplet (deformation, internal flow, fragmentation, and so forth [3]). Recently, we carried out the three-dimensional hydrodynamic simulation taking into account the droplet rotation and succeeded to re-produce the external shape of prolate chondrules [4]. However, in this previous paper, we did not consider the high-viscosity just before solidification.

In this study, we simulate the rotating viscous droplet exposed to the gas flow in the framework of the shock-wave heating model. Here we report that the external shape of prolate chondrules in group-B can be re-produced with the appropriate rotation rate and the gas ram pressure. In addition, we discuss the condition to re-produce the prolate chondrule shape by analytic method. Our results strongly suggest that the existence of such prolate chondrules is a strong evidence of shock-wave heating events in the early Solar nebula.

Model: We initially assume that the completely molten droplet exposed to the uniform gas flow is rotating with a constant angular velocity ω. The rotation axis is perpendicular to the direction of the gas flow [4]. The ram pressure of the gas flow is set as $p_{\mathrm{fm}} = 10^4\,\mathrm{dyne\,cm^{-2}}$, which can be considered in the shock-wave heating model. The initial droplet shape is a perfect sphere with the radius of $r_0 = 1\,\mathrm{mm}$. The surface tension is $\gamma_{\mathrm{s}} = 400\,\mathrm{dyne\,cm^{-1}}$. The viscous coefficient is $\mu = 1000\,\mathrm{g\,cm^{-1}\,s^{-1}}$ for just before solidification. The initial angular velocity is a free parameter ($\omega = 1 - 1000\,\mathrm{s^{-1}}$) in this study. The details of our numerical scheme is described in our recent paper [3].

Numerical Results: We show a simulation result in a case of $\omega = 100\,\mathrm{s^{-1}}$. The gas flow points to the x-direction and the rotation axis is the z-axis in this study. Fig. 1 shows the xy-section (perpendicular to the rotation axis, left panel) and xz-section (parallel with the rotation axis, right panel) of the droplet about 5 seconds later since the initial state. In the left panel, we can see that the droplet shrinks perpendicularly to the rotation axis. In contrast, in the right panel, the droplet elongates along the rotation axis because of the conservation of volume. It is a prolate shape. Fig. 2 shows the three-dimensional view of the same result. The shape does not change significantly even if the calculation continues farther. Therefore, we consider that the prolate shape is a final droplet shape in this case. The axial ratios of the final droplet shape are about C/B ~ 0.94 and B/A ~ 0.76. These values are very similar to the group-B chondrules.

Discussions: Why does the droplet shape become prolate shape? The reason is very simple. It is considered that the droplet just before solidification is highly viscous. Such high-viscous droplet cannot deform rapidly than it rotates. In other words, the area of the droplet surface where the ram pressure affects on is moving by the rotation before the droplet completely deforms by the gas flow from fixed direction. In this case, the time-averaged gas flow becomes the axis-symmetry about the rotation axis. Therefore, the droplet becomes a prolate shape with the major axis parallel with the rotation axis.

However, it should be noted that the droplet shape does not become the prolate shape if the angular velocity is too large. In this case, the centrifugal force influences so that the droplet becomes an oblate shape. This suggests that there is an upper limit of the angular velocity to re-produce the group-B (prolate) chondrules. In order to obtain the upper limit of the angular velocity, we derive the droplet deformation by an analytic method.

We analytically derive the linear solution of the droplet shape assuming that the gas flow is axis-symmetry about the rotation axis. We solve the hydrodynamical equations of the molten droplet assuming that the non-linear terms of the hydrodynamical equations as well as the surface deformation are sufficiently small so that the linearized equations are appropriate, which is the same approach adopted by the previous study [5]. According to our linear solution, the droplet shape can be determined by only two non-dimensional parameters: the Weber number $W_e \equiv p_{\rm fm} r_0 / \gamma_{\rm s}$ and the normalized centrifugal force $R \equiv \rho \omega^2 r_0^2 / \langle p_{\rm fm} \rangle$, where ρ is the material density of the droplet and $\langle p_{\rm fm} \rangle$ is the time-averaged gas ram pressure. If $R < 19/5$, the droplet shape becomes a prolate shape. If $R > 19/5$, it becomes a oblate shape because of the strong centrifugal force. When $R = 19/5$, the droplet shape is a perfect sphere. Fig. 3 shows the conditions for re-producing the external shapes of group-A and -B as a function of W_e and R. The horizontal axis is R and the vertical one is W_e. A vertical dashed line indicates the critical value of R ($R_{\rm cr} = 19/5$), so the left region of the dashed line indicates the prolate shape and the right region indicates the oblate shape. The solid curves in the left region are the contours of the axial ratio B/A of 0.9, 0.8, 0.7, and 0.6. In this diagram, the blue (red) region indicates the condition to re-produce the external shapes of group-A (-B) chondrules. In addition, the grayed region indicates that the droplet shape is unstable because of the rapid rotation [6]. According to Fig. 3, we find that the largely-elongated prolate shape (like group-B chondrules) can be explained by a relatively small R (less than about unity) and an appropriate W_e (~ 2 - 3). In contrast, the strongly-flattened oblate shape cannot be explained because of the shape instability. These results show a good agreement with the actual chondrule shape distribution.

Conclusions: In this study, we reported that the rotating viscous droplet exposed to the high-velocity gas flow becomes the prolate shape with an appropriate range of the angular velocity. The aspect ratio of the prolate shape increases (largely-elongated) as the Weber number increases. We found that the prolate chondrules measured by [1] can be explained in the framework of the shock-wave heating model. Our results strongly suggest that the existence of the prolate chondrules might be a strong evidence of the shock-wave heating events in the early Solar system.

References: [1] Tsuchiyama A., et al. (2003) *LPS XXXIV*, 1271-1272. [2] Iida A., et al. (2001) *Icarus*, 153, 430-450. [3] Miura H., and Nakamoto T., (2006), *Icarus*, in press (astro-ph/0611289). [4] Miura H., and Nakamoto T., (2006) *LPS XXXVII*, 1765-1766. [5] Sekiya M., et al. (2003) *Prog. Theo. Phys.*, 109, 717-728. [6] Chandrasekhar S., (1965) *Proc. Roy. Soc. London, A.*, 289, 1-26.

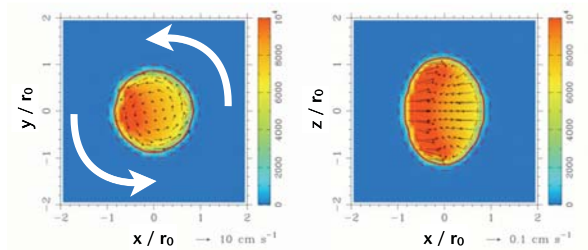

Fig. 1: The snap shots of the hydrodynamic simulation of rotating viscous droplet exposed to the gas flow. The left (right) panel is the section of xy- (xz-) plane. The gas flow comes from the left side. Color contour shows the hydrostatic pressure inside the droplet.

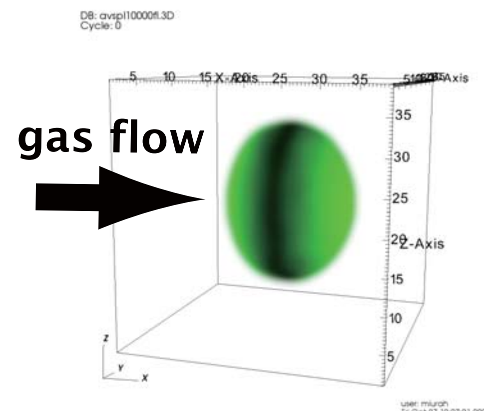

Fig. 2: Three-dimensional view of the same result as Fig. 1. The rotation axis is parallel with the vertical axis in this figure.

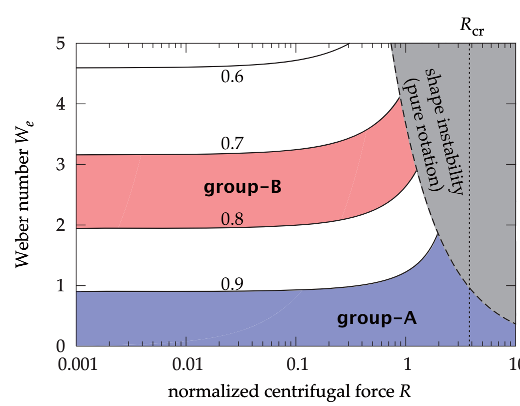

Fig. 3: The conditions to re-produce the group-A and -B chondrules. The horizontal axis is the normalized centrifugal force R and the vertical axis is the Weber number W_e.