Shock Wave in Solar Nebula: Evidence and Application for Dust Thermal Processing

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ABSTRACT: Chondrules are millimeter-sized and spherical-shaped grains which are abundant in primitive meteorites (chondrites). They are believed to have been formed in the early solar nebula from once-molten millimeter-sized silicate dust particles (droplets) due to the instantaneous heating, however, the physical/chemical environments for the chondrule formation have been controversial over 100 years or more. Here we report the evidence of the gas frictional heating for chondrule formation through consideration to the origin of chondrule shapes which are not perfectly spherical. Actually, the external shapes of some chondrules measured by the X-ray computed tomography (CT) showed largely-deformed prolate shape (like a rugby-ball). We found that the prolate shape can be explained by the deformation of rotating viscous droplet exposed to the high-velocity gas flow. Our results strongly suggest that shock waves were frequently generated in the solar nebula and heated the mm-sized dust particles up to their meting points.

Fig.1 Dust Melting in Solar Nebula
- gas disk containing dust particles

Fig.2 Chondrules
- mm-sized spherical bodies in chondritic meteorites
- Formation mechanism have been controversial for long time

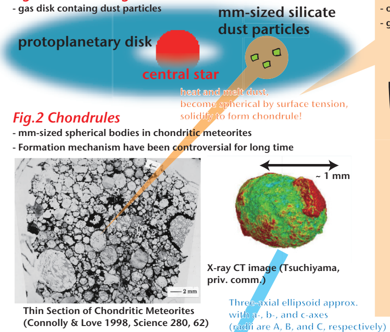


Fig.4 Shock-Wave Heating Model
- one of the most plausible models for chondrule formation
- gas frictional heating after passing through shock front

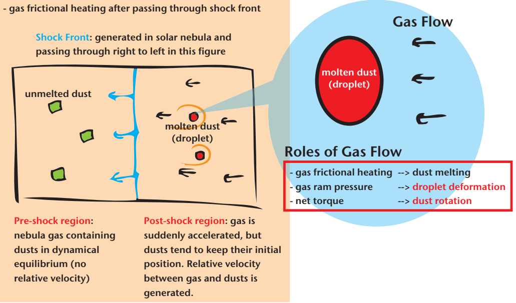


Fig.6 Why Prolate?
If droplet rotates much faster than its deformation timescale, the effect of gas ram pressure can be approximated as axis-symmetry by taking a time-average.

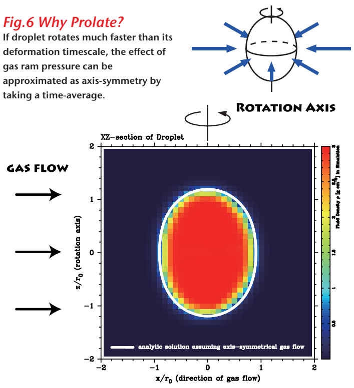


Fig.3 Largely-elongated Prolate Shape
- Why is the shape apart from sphere?
- key issue to understand the chondrule formation

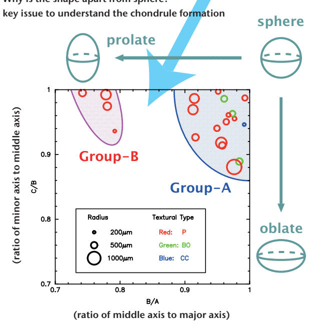
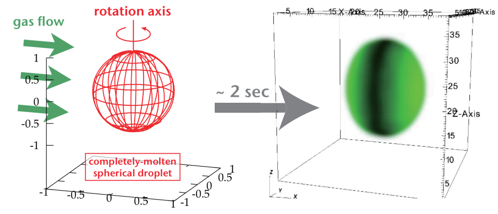


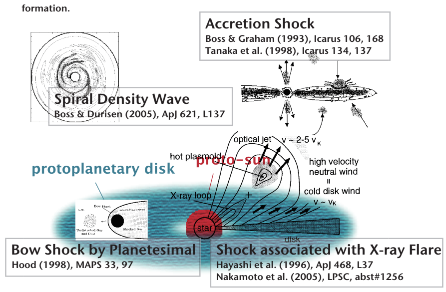
Fig.5 3-D Hydrodynamic Simulation of Droplet Deformation



Initial settings: perfectly-spherical rotating droplet exposed to gas flow. Rotation axis is assumed to be perpendicular to gas flow.

After ~ 2sec: largely-elongated prolate shape. Major axis is parallel with rotation axis. Axial ratios B/A and C/B is very similar to prolate chondrules.

Fig.7 Shock Generation in Solar Nebula
There are some candidates for shock generation mechanism in solar nebula. Our results can be used for considering which mechanism is suitable for chondrule formation.



1 Dust Melting in Solar Nebula

Chondrules are millimeter-sized and spherical-shaped grains which are abundant in primitive meteorites (chondrites, see Fig.2). They are believed to have been formed in the early solar nebula from once-molten millimeter-sized silicate dust particles (droplets) due to the instantaneous heating [1] (see Fig.1), however, the heating mechanism for chondrule formation have been controversial over 100 years or more [2]. What mechanism was sufficient to heat the silicate dust particles up to their melting point ($T_{\rm melt} \gtrsim 1600\,{\rm K}$)? In order to elucidate this riddle, some theoretical models have been proposed: the gas frictional heating induced by shock waves [3, 4, 5, 6, 7] , the direct irradiation by the central star [8], the electric discharge in the solar nebula [9], and so forth. However, no model has not explained all of physical/chemical features of chondrules yet. The chondrule formation is now an ongoing subject.

2 Prolate Shape

Some chondrules show largely-elongated prolate shapes. The three-dimensional shapes were measured by X-ray micro-tomography [10]. Their external shapes were approximated as three-axial ellipsoids with a-, b-, and c-axes (axial radii are A, B, and C ($A \geq B \geq C$), respectively) using the moments of inertia of the chondrule shapes. Fig.3 shows the plot of C/B vs. B/A for chondrules. We found that the chondrule shapes can be classified into two groups: oblate to prolate chondrules with B/A and C/B close to unity (group-A) and largely-enlongated prolate chondrules with $B/A \sim 0.7-0.8$ (group-B). It is considered that external shapes of chondrules reflect the droplet shapes just before they solidified to form chondrules.

3 Dust Heating by Nebula Shock

The shock-wave heating model is one of the most plausible models for chondrule formation (see Fig.4). Let us suppose there is a gas medium containing dust particles in dynamical equilibrium; i.e., they do not have a relative velocity initially. And let us suppose a shock wave passes through the medium. In the post-shock region, the gas is accelerated by the gas pressure and obtains some amount of velocity, while dust particles tend to remain at the initial position. This causes a relative velocity between the dust particles and the gas. For appropriate shock conditions (shock velocity and pre-shock gas number density), dust particles are heated up to their melting points and change into chondrules [4].

One of the remarkable features of this model is the gas ram pressure on the dust particles. It causes the deformation of molten droplets [11, 12]. In addition, it produces the net torque on unmelted dust particles because of their irregular shapes and rotates them. The rotating droplet exposed to the gas flow might be deformed to prolate shapes. In order to confirm this hypothesis, we carry out the three-dimensional hydrodynamic simulation of the mm-sized molten silicate dust particles, which are rotating and exposed to high-velocity gas flow.

4 3-D Hydrodynamic Simulation

The 3-D hydrodynamic equations are the equations of continuity (EOC) and momentum (EOM). In addition, the equation of state (EOS) is used to close the equations.

$$\text{EOC:} \quad \frac{\partial \rho}{\partial t} + \boldsymbol{\nabla} \cdot (\rho \boldsymbol{u}) = 0, \tag{1}$$

$$\text{EOM:} \quad \frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u} \cdot \boldsymbol{\nabla}) \boldsymbol{u} = \frac{-\boldsymbol{\nabla} p + \mu \Delta \boldsymbol{u} + \boldsymbol{F}_{\rm s} + \boldsymbol{F}_{\rm g}}{\rho}, \tag{2}$$

$$\text{EOS:} \quad \frac{dp}{d\rho} = c_{\rm s}^2, \tag{3}$$

where ρ, $\boldsymbol{u}$, p, μ, and $c_{\rm s}$ are the mass density, velocity, pressure, viscosity, and sound speed of the droplet, respectively. $\boldsymbol{F}_{\rm s}$ and $\boldsymbol{F}_{\rm g}$ are the surface tension and gas ram pressure, respectively. The numerical scheme we adopted for solving EOC is the R-CIP-CSL2 scheme, which guarantees the exact conservation even in the framework of a semi-Lagrangian scheme [13]. The non-advection phase of EOM is solved by using the C-CUP scheme, which is one of the powerful schemes to solve the multi-phase fluids (incompressible and compressible) [14]. Details of our numerical scheme can be seen in [12].

Initial Settings for Calculation: gas ram pressure $p_{\rm fm} = 10^4\,{\rm dyne\,cm^{-2}}$ and and angular velocity $\omega = 100\,{\rm rad\,s^{-1}}$ are estimated from the shock-wave heating with chondrule-forming conditions, unperturbed droplet radius $r_0 = 1\,{\rm mm}$ is typical value for chondrules, and surface tension $\gamma_{\rm s} = 400\,{\rm dyne\,cm^{-1}}$, mass density $\rho_{\rm d} = 3\,{\rm g\,cm^{-3}}$, and viscosity $\mu_{\rm d} = 10^3\,{\rm g\,cm^{-1}\,s^{-1}}$ of the droplet are typical values for silicate melts (also see Fig.5).

5 Results

On starting the calculation, the droplet begins to elongate along the rotation axis (see Fig.5). The droplet shape becomes slenderer as the time elapses, and finally the deformation ceases after $\sim 1\,{\rm sec}$. The shape does not change significantly after that. The final droplet shape is prolate, with the major axis parallel with the rotation axis. Its axial ratios are $B/A \simeq 0.77$ and $C/B \simeq 0.95$, respectively. It should be noted that the final droplet shape is very similar to the group-B prolate chondrules in their axial ratios.

6 Why Prolate?

The droplet viscosity just before solidification is very large, so the droplet deformation proceeds very slowly. In our simulation, the time scale of the droplet deformation ($\sim 1\,{\rm sec}$) is much longer than the rotation period ($= 2\pi/\omega \sim 0.06\,{\rm sec}$). In this case, the effect of the gas ram pressure can be approximated as axis-symmetry by taking a time-averaged over its deformation time scale (see Fig.6). In such situation, we can derive the external shape of the droplet by analytically solving the axis-symmetrical hydrodynamic equations with appropriate boundary conditions (analytic procedures can be seen in [11]). We obtain the analytic formula of the deformed droplet radius $r_{\rm s}(\theta)$ as

$$r_{\rm s}(\theta) = r_0 \Big[1 + W_e (R_{\rm cr} - R) P_2(\cos\theta)/12 \Big], \tag{4}$$

where θ is the polar angle and $P_n(\cos\theta)$ is the Legendre function ($n=2$ in Eq. 4). It is found that the droplet shape depends only on two non-dimensional parameters: the Weber number W_e defined by

$$W_e \equiv p_{\rm fm} r_0 / \gamma_{\rm s}, \tag{5}$$

which indicates the ratio of the gas ram pressure to the surface tension of the droplet, and the centrifugal force normalized by the gas ram pressure R defined by

$$R \equiv \rho \omega^2 r_0^2 / p_{\rm fm}. \tag{6}$$

$R_{\rm cr} = 19/20$ is the critical value of R. Our numerical simulation shows an excellent agreement with the analytic formula (Eq. 4).

7 Summary

We carried out the three-dimensional hydrodynamic simulations of mm-sized molten silicate dust particles, which is rotating and exposed to the high-velocity gas flow. We found that the droplet shape becomes largely-elongated prolate shape and is very similar to some chondrule samples. Our results strongly suggest that shock waves were generated in solar nebula to form such deformed spherical bodies observed in chondritic meteorites. Some theoretical models for shock generation in solar nebula were proposed by many authors (see Fig.7). We consider that such nebula shocks should play an important role for the dust thermal processing in our solar nebula.

References: [1] Jones et al. (2000), in *Protostars and Planets IV* (eds Mannings, V., Boss, A. P. & Russell, S. S.), 927-962 (Univ. of Arizona Press, Tucson, 2000). [2] Sorby (1877), *Nature* **15,** 495-498. [3] Hood & Horanyi (1991), *Icarus* **93,** 259-269. [4] Iida et al. (2001), *Icarus* **153,** 430-450. [5] Desch & Connolly (2002), *Meteorit. Planet. Sci.* **37,** 183-207. [6] Ciesla & Hood (2002), *Icarus* **158,** 281-293. [7] Miura & Nakamoto (2006), *ApJ.* **651,** 1272-1295. [8] Shu et al. (2001), *ApJ.* **548,** 1029-1050. [9] Pilipp et al. (1992), *ApJ.* **387,** 364-371. [10] Tsuchiyama et al. (2003), *Lunar Planet. Sci. Conf.* **XXXIV,** abstr. 1271 [CD-ROM]. [11] Sekiya et al. (2003), *Prog. Theo. Phys.* **109,** 717-728. [12] Miura & Nakamoto (2007), *Icarus* **188,** 246-265. [13] Nakamura et al. (2001), *J. Comp. Phys.* **174,** 171-207. [14] Yabe & Wang (1991), *J. Phys. Soc. Jpn.* **60,** 2105-2108.

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