Shock-Wave Heating Model for Chondrule Formation: Appropriate Conditions in Protoplanetary Disk.

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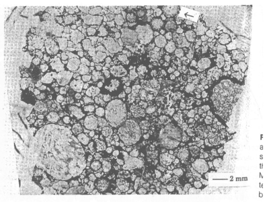
1. ABSTRACT

SHAPE OF CHONDRULES AND MOLTEN DROPLET IN HIGH-VELOCITY GAS FLOW

It is believed that silicate spheric component in chondritic meteorites (chondrule) is the evidence of dust melting event in the protoplanetary disk in early stage of the planet formation. Chondrules have various properties (e.g., size, shape, chemical composition, and so forth) and the theoretical model for chondrule formation must can explain all of these properties. One of the most plausible model is shock-wave heating model (see right figure). In this model, the molten droplet would be exposed to the high-velocity rarefied gas flow. Therefore, the deformation of droplet is naturally expected. In this paper, we report 3-D hydrodynamic simulation of molten droplet which is exposed to the gas flow and discuss relation with chondrule shapes.

Chondrule

~ dust melting event in the protoplanetary disk ~



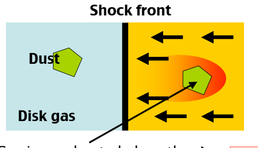
Thin section of chondritic meteorite (Connolly & Love 1998)

Spherical structures in left figure are chondrules. Typical radius is a few 100 mm and mainly composed of silicate. It is believed that chondrules are the evidence of dust melting event in the protoplanetary disk.

Shock-Wave Heating Model

~ one of the most plausible model for chondrule formation ~

Dust particles in protoplanetary disk can be heated when shock waves are generated



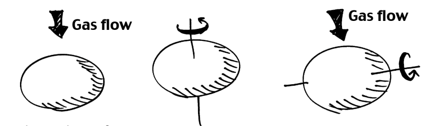
Gas is accelerated abruptly, but not for dust particles ▶ Gas frictional heating

This model can explain various observational constraints for chondrule formation (e.g., Iida et al. 2001). The dust particle is exposed to the gas after passing though the shock front. The gas frictional force (dynamical effect) takes place on the dust particle, as well as the gas frictional heaitng (thermal processing).

2. INTRODUCTION (1)

DEFORMATION, DYNAMICS OF DROPLET

Ram pressure	Rotation	Ram pressure + Rotation
Sekiya et al. (2003) Uesugi et al. (2003)	Susa & Nakamoto (2002) Tsuchiyama et al. (2003)	

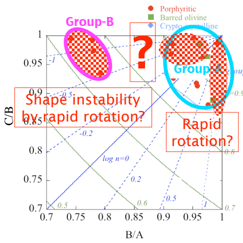


Analytic solution for small deformation has been obtained (Sekiya et al 2003).

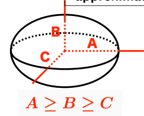
Effect of rotation is important (Tsuchiyama et al. 2003). But, it has not been investigated yet.

3. INTRODUCTION (2)

THREE-DIMENSIONAL STRUCTUR



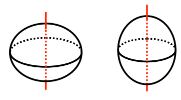
3-axial ellipsoid approximation



$A \geq B \geq C$

Tsuchiyama et al. (2003) measured 3-dimensional chondrule shape. They derived each radius (A, B, C) by approximating chondrule shape as 3-axial ellipsoid.

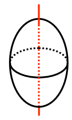
Group-A



Oblate, prolate, and general 3-axial ellipsoid. Relatively small deformation (B/A, C/B > 0.9)

Ram pressure or rotation can produce oblate chondrules? The origin of prolate chondrules has not well discussed.

Group-B



Prolate. Relatively large deformation (B/A ~ 0.75)

Shape instability by rapid rotation?

▼

Deformation is too small!

4. PURPOSE, MODEL, and METHOD

ELUCIDATION OF DYNAMICS OF DROPLET BY HYDRODYNAMIC SIMULATION

We investigate the dynamics of molten droplet in shock-wave heating by numerical method. Especially, in this study, we focus

Rotating Droplet exposed to the Gas Flow.

Numerical scheme : CIP method ✚ Pressure-Based Algorithm

Hydrodynamic Eqs.

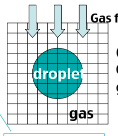
$$\frac{\partial \rho}{\partial t} + \boldsymbol{u}\cdot\nabla\rho = -\rho\nabla\cdot\boldsymbol{u},$$

$$\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u}\cdot\nabla\boldsymbol{u} = -\frac{\nabla p}{\rho} + \Omega,$$

$$\frac{\partial p}{\partial t} + \boldsymbol{u}\cdot\nabla p = -\rho c_s^2\nabla\cdot\boldsymbol{u},$$

Advection term --- CIP method

Non-advection term --- Pressure-based algorithm



60x60x60 Cartesian grid

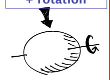
External forces:

Viscosity μ = 1.3 poise s
Surface tension σ = 400 dyne cm^{-1}
Ram pressure P_{fm} = 4000 dyne cm^{-2}

CIP (Constrained Interpolation Profile) method is the numerical scheme for advection equations with third-order accuracy. It is one of the most powerful tools for multi-phase fluid analysis (Yabe et al. 2001).

Pressure-based algorithm is adopted to solve incompressible fluid dynamics. First, the pressure field is solved implicitly. After that, the eq. of motion and eq. of continuity are solved.

Estimation of angular velocity



Asymmetrical shape of dust → Is net torque acting on it?

Angular momentum gained for the duration Δt

$$I\Omega \sim f\pi a^2 F_{gas} a \Delta t$$

$$\Delta t \sim \frac{1}{2}\frac{\pi}{\Omega}$$

I : moment of inertia, Ω: angular velocity, a : dust radius

Degree of asymmetry (we use f = 0.02, 0.10, 0.50 in this study)

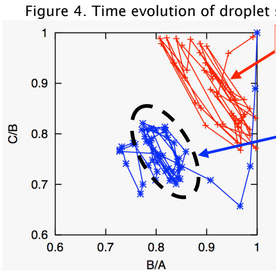
$$\Omega \sim 200\left(\frac{f}{0.1}\right)^{1/2}\left(\frac{F_{gas}}{4000\,\mathrm{dyne\,cm^{-2}}}\right)^{1/2}\left(\frac{a}{1\,\mathrm{mm}}\right)^{-1}\mathrm{s}$$

5. RESULT (1)

TIME SCALE OF ROTATION AND INTERNAL FLOW

Initial shape of droplet is a perfect sphere (B/A = 1, C/B = 1). As soon as the calculation starts, the droplet is deformed due to the effects of ram pressure and rotation, so the axial ratios B/A, C/B also evolve with time (see bottom figure 4).

Figure 4. Time evolution of droplet shape



Small Droplet (radius 200μm)

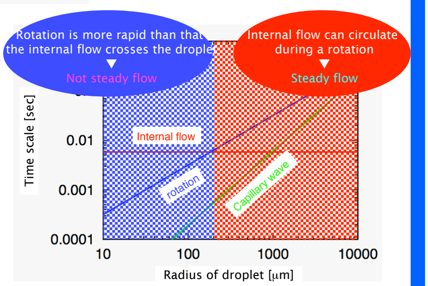
The deformation continues with time (oblate, prolate, and general three-axial ellipsoid). Steady shape is not established.

Large Droplet (radius 1000μm)

First, it deforms rapidly to oblate. After a certain amount of time passes, the shape settles into a certain general three-axial ellipsoid. After that, although small vibration around the settling shape exists, it does not deform more.

We can understand the difference of behavior by considering the time scales of internal flow and rotation. The dependences of these two time scales on the dust size are different each other.

We estimate the internal flow time scale as the crossing time $t_{flow} = D / v_{flow}$, where D is the dust diameter and v_{flow} is the velocity of the internal flow (Sekiya et al. 2003).



6. RESULT (2)

DEPENDENCE ON ROTATION VELOCITY FOR DROPLET SHAPES

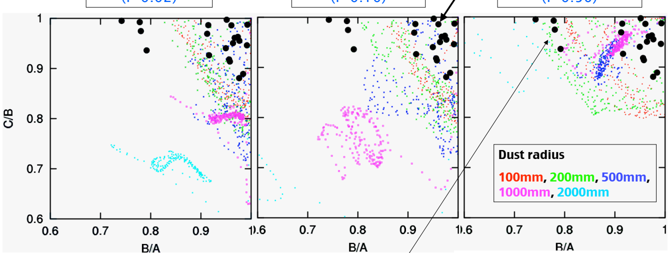
We consider the rotation of dust particle which originates in the asymmetrical shape of the dust particle. The expected angular velocity depends on the degree of asymmetry f. We investigate how the time evolution of the droplet shape is affected when f is changed.

f The degree of asymmetry of dust shape (non-dimensional)

In bottom panels, we plot the time evolution of axial ratios B/A and C/B with constant time interval. Namely, the scattered distribution of plots means that the droplet keeps the shape for very short duration. On the contrary, the dense distribution means that the droplet can keep the shape for long time.

Data by Tsuchiyama et al. (2003)

Slow rotation (f=0.02)	Standard case (f=0.10)	Rapid rotation (f=0.50)



Ram pressure dominates ▼ Kind of Oblate

The shape of Group-B can be reproduced (f=0.5). However, other axial ratios should be produced! (why are such chondrules not observed?)

Rotation dominates ▼ Kind of Prolate

Future work: We simulate the deformation of droplet in the gas flow and compare our results with measured chondrules in shape. However, chondrule shape is the result of re-solidification. Therefore, in the future, we must discuss the effect of re-solidification on the hydrodynamics of molten droplet.

SUMMARY

1. The time evolution of droplet changes qualitatively depending on the droplet size. The difference of behavior can be understood by considering the time scales of internal flow and rotation.
2. Not only oblate shape but also prolate and general three-axial ellipsoid can be reproduced.
3. We could not clearly explain the origin of Group-B chondrules.

REFERENCES

[1] Ciesla & Hood 2002, Icarus 158, 281. [2] Connolly & Love 1998, Science 280, 62. [3] Desch & Connolly 2002, Meteorit.Planet.Sci. 37, suppl. A41. [4] Hood & Horanyi 1991, Icarus 93, 259. [5] Iida et al. 2001, Icarus 153, 430. [6] Miura et al. 2002, Icarus 160, 258. [7] Miura & Nakamoto 2005, Icarus 175, 289. [8] Ruzmaikina & Ip 1994, Icarus 112, 430. [9] Sekiya et al. 2003, Prog.Theo.Phys. 109, 717. [10] Susa & Nakamoto 2002, ApJ 564, L57. [12] Tsuchiyama et al. 2003, Lunar and Planetary Science Conference, abstract#1271. [13] Uesugi et al. 2003, Earth, Planets and Space 55, 493. [14] Yabe et al. 2001, J.Comp.Phys. 169, 556.

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