Experimental Study on Collisional Disruption of Core-Mantle bodies

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Introduction

- Formation of protoplanets by collisional growth of planetesimals in the solar nebula

- Thermal evolution of planetesimals
  - formation of core-mantle structure

  - rock core-porous mantle body
    - pressure sintering

  - metal core-rock mantle body
    - melting and gravitational differentiation of the constituent materials
We should consider a collisional phenomenon not only for homogenous bodies but also for rock core-porous mantle bodies in order to study the planetary accretion process.

The importance of impact experiments on core-mantle bodies
- There could be many rock core-porous mantle bodies in the initial stage of planetary accretion process.
- The difference of physical properties between homogenous bodies and core-mantle bodies could result the difference of collisional disruption.

A lot of experiments and numerical simulations on the impact disruption of homogenous materials by previous studies
- There are a little studies about the impact disruption of core-mantle bodies.

We should consider a collisional phenomenon not only for homogenous bodies but also for rock core-porous mantle bodies in order to study the planetary accretion process.
purpose of our study

-To investigate the impact strength and the fragment velocity distribution of rock core-porous mantle bodies in order to **clarify the reaccumulation condition of core-mantle bodies.**

In this study, we measured **the fragment size distribution of the silicate core-porous mantle body**, which is shown here, and measured **the fragment velocity distribution** by using high speed photography.
Impact velocity: 1.5-4.6 km/s
Projectile (Nylon): 7 mg and 190 mg

Experimental Impact experiment
> 2-stage light gas gun
  Impact velocity: 1.5-4.6 km/s
  Projectile (Nylon): 7 mg and 190 mg

Observation
> Image-converter camera
  1 x 10^4 - 5 x 10^5 frames/s (15 frames)
> High speed digital video camera
  4 x 10^3 - 2 x 10^4 frames/s
Sample preparation

Target; Glass core-Gypsum mantle target

- Target mass: 0.46-35 g
- Energy Density: $1 \times 10^3 - 4 \times 10^4$ J/kg
- Glass sphere diameter: 0-25 mm
- Gypsum layer thickness: 0-14 mm

<table>
<thead>
<tr>
<th>Sample</th>
<th>Density (g/cm³)</th>
<th>Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td>2.5</td>
<td>~0%</td>
</tr>
<tr>
<td>Gypsum</td>
<td>1.1</td>
<td>~55%</td>
</tr>
</tbody>
</table>
Analytical Method for Fragment Velocity of core-mantle bodies

by high speed digital video camera

Projectile mass; 7 mg  Impact velocity; 3.2 km/s
Largest Fragment Mass vs. Energy Density

The change of CMR and $t_m/d_p$

Basalt line
(Fujiwara and Tsukamoto, 1980)

Gypsum line
(This study; Kawakami et al., 1991)

Glass
(Gault & Wedekind, 1969)

Core-Mantle target

Glass target

Largest Fragment Mass, $m_l/M_t$

Energy Density, $J/kg$
Type of disruption for core-mantle bodies

- Core disruption
- Mantle Disruption or Cratering

- Normalized Gypsum Thickness, \( t_m/d_p \)
- Energy Density, \( J/kg \)

- gypsum
- glass

Core disruption

Mantle Disruption

Cratering
Largest Glass Fragment Mass vs. Mantle thickness

Normalized Gypsum Thickness, \( t_m/d_p \)

Energy density for target:
- \( 16000-30000 J/\text{kg} \)
- \( 6000-10000 J/\text{kg} \)
- \( 3000-5500 J/\text{kg} \)
- \( 1000-2500 J/\text{kg} \)

Core nondisruption

Core disruption
**Largest Fragment Mass vs. Energy Density**

- **Glass** (Gault & Wedekind, 1969)
- **Basalt line** (Fujiwara and Tsukamoto, 1980)
- **Gypsum line** (This study; Kawakami et al., 1991)

Graph showing the relationship between Largest Fragment Mass and Energy Density.
The energy density for core ($Q_g$) is given by:

$$Q_g \cdot M_g = E_c$$

And the specific energy $f_c$ is:

$$f_c = \frac{E_c}{E_k}$$

Where $E_c$ is the energy of core, $E_k$ is the kinetic energy, $V_i$ is the velocity, $E_c$ is the energy of displaced materials, and $M_g$ is the mass of displaced materials.
Energy partition rate for glass core, $f_c$

\[ f_c = \frac{E_c}{E_k} \]

Partition coefficient of kinetic energy partitioned into glass core

\[ y = 1.7819 \times e^{-2.3295x} \quad R^2 = 0.68906 \]
Largest Fragment Mass vs. Core Mass Ratio

Largest Fragment Mass, $m_l/M_t$ vs. Core Mass Ratio

Core Mass Ratio

Largest Fragment Mass, $m_l/M_t$
Core non-disruption vs. Core Mass Ratio

Largest Fragment Mass, $m_l/M_t$ vs. Core Mass Ratio
Largest Fragment Mass vs. Core Mass Ratio

Core disruption

Core non-disruption

Largest Fragment Mass, $m_l/M_t$

Core Mass Ratio

CMR Line
Experimental results of Fragment Velocity at various position form Impact Point

Impact Point

Core-Mantle target

Antipodal point

CMR=1
CMR=0.638
CMR=0.245
CMR=0.531
CMR=0.046

Experimental results of Fragment Velocity at various position form Impact Point

Vejecta m/s

Angle, degree
Antipodal Velocity vs. Energy Density

\[ V_{\text{ant}} = f(R_c) \cdot g(Q) \]

CMR = 0.6-0.8
CMR = 0.4-0.6
CMR = 0.01-0.3
CMR = 0

Basalt line
(Fujiwara and Tsukamoto, 1980)

Gypsum line
(this work)
Sample preparation

**Measurement of particle velocity \((u_p)\) attenuation in Gypsum targets and Two-layered targets**

Sample; Gypsum plate and two-layered plate

Gypsum plate 1.9-12 mm

Two-layered plate

- Gypsum plate 1.5-5.5 mm
- Glass plate 2.0 mm

\[ V_{\text{ant}} \approx 2u_p \]
Antipodal Velocity vs. Plate thickness for Gypsum Plate and Two-layered plates

What happened in two layered plates?

$V_{ant}/V_i \propto \left( \frac{r}{d_p} \right)^{-3.9}$

$P \approx \rho C_0 \left( \frac{V_{ant}}{2} \right)$
Shock Pressure attenuation model in two-layered body

Small shock pressure attenuation

Glass region

Normalized Shock pressure

Normalized Target Thickness

Shock pressure attenuation

isobaric core

$t_{tr}/d_p < 1.5$

Shock pressure attenuation

Gypsum Plate

Two-layered Plate

$P \approx \rho C_0 \left( \frac{V_{ant}}{2} \right)$

$P \propto \left( \frac{r}{d_p} \right)^{-3.9}$

$\frac{P}{V_i} \propto \left( \frac{r}{d_p} \right)^{-3.9}$

Normalized Shock pressure

Normalized Target Thickness
Calculation results of Fragment Velocity

- Impact point
- 90°
- 60°
- 54°
- 30°
- Antipodal point

Fragment Velocity

- CVR = 0.89, \( t_m/d_p = 25\text{mm} \)
- CVR = 0.72, \( t_m/d_p = 6\text{mm} \)
- CVR = 0.31, \( t_m/d_p = 14\text{mm} \)
- CVR = 0.088, \( t_m/d_p = 20\text{mm} \)

Angle, degree

Ve/Vi

0 20 40 60 80

0 0.1 1

2.5mm

6mm

14mm

20mm

60mm

Antipodal point

Impact point
**Calculation results of Fragment Velocity at various position from Impact Point**

![Graph showing calculation results of Fragment Velocity at various position from Impact Point.](insert_graph)

**Experimental results of Fragment Velocity at various position from Impact Point**

![Graph showing experimental results of Fragment Velocity at various position from Impact Point.](insert_graph)
Summary-1

- The Largest Fragment Mass of core-mantle body depends on energy density, mantle thickness and CMR.

- We estimated the energy partitioned into the glass core.

- The energy partition coefficient of the glass core depends on the mantle thickness.

- Largest fragment mass depends on CMR at the constant energy density. However, the relationship among antipodal velocity, CMR and mantle thickness is complex.
Summary-2

- **Antipodal velocity of core-mantle bodies depends on energy density, mantle thickness and CMR.**

  - We obtained the empirical equation about the antipodal velocity, energy density and CMR.

  \[
  V_{\text{ant}} = C_0 \exp(a \ R_c) \ Q^n
  \]

  \[
  a=2 - 5, \ n=0.5 - 0.8
  \]

  - The calculation results by the shock wave attenuation model in two-layered target showed good agreement with the velocity distribution of core-mantle target examined in this study.
Normalized Total Gypsum Thickness, $t_m/\Delta p$

Core nondisruption

$y = 0.024007 \times e^{-0.19902x}$  \( R = 1 \)

$y = 0.0083002 \times e^{-0.3605x}$  \( R = 0.89237 \)

$y = 0.064001 \times e^{-1.8535x}$  \( R = 0.98517 \)

Core disruption

$y = 3000-37000\, \text{J/kg}$

$y = 16000-24000\, \text{J/kg}$

$y = 6000-10000\, \text{J/kg}$

$y = 3000-5500\, \text{J/kg}$

$y = 1000-2500\, \text{J/kg}$

$V_{\text{An}}/V_{\text{i}}$

$30000-37000\, \text{J/kg}$

$16000-24000\, \text{J/kg}$

$6000-10000\, \text{J/kg}$

$3000-5500\, \text{J/kg}$

$1000-2500\, \text{J/kg}$
Antipodal Velocity vs. Core Mass Ratio

\[ V_{\text{ant}} = f(R_c) \cdot g(Q) \]
Normalized Gypsum Thickness, $t_m/d_p$

Energy Density, J/kg

- 15,000-25,000 J/kg
- 4,000-6,000 J/kg
- 1,800-2,000 J/kg
- 1,000-1,300 J/kg
- 600-800 J/kg
- 400-500 J/kg
- <400 J/kg

Core Disruption

Mantle Disruption or Cratering
$y = 159.81 \times e^{(-3.0609 \times 10^{-6}x)} \quad R = 1$

$y = 14.862 \times e^{(8.1168 \times 10^{-5}x)} \quad R = 0.97734$

$y = 10.689 \times e^{(5.2435 \times 10^{-5}x)} \quad R = 0.89717$

$y = 2.9925 \times e^{(0.00011131x)} \quad R = 0.98778$

$y = 2.393 \times e^{(0.0002765x)} \quad R = 1$

$y = 4.2412 \times e^{(9.3586 \times 10^{-5}x)} \quad R = 0.93943$
Fragmental size distribution

Gypsum sample + Glass sample

Homogenous target
CMR = 0.1

Gypsum

Glass

Normalized fragment mass, m/Mt

Cumulative Number

Fig. 5: The fragment size distribution of gypsum, glass, and core-mantle body

Gypsum + Glass

Core-mantle target

CMR = 0.40

Largest fragment mass

Gypsum mass = 3.7g
Glass mass = 2.5g
Vi = 3.4 km/s

Normalized fragment mass, m/Mt

y = 0.065912 * x^(-0.95947)  R = 0.99693

Gypsum + Glass

Largest fragment

vi = 3.4 km/s

Largest fragment

vi = 3.4 km/s
CMR = 0.7 - 0.85
CMR = 0.4 - 0.6
CMR = 0.2 - 0.36
$y = 6.9619 \times e^{(4.8026x)} \quad R = 1$

$y = 10.486 \times e^{(2.6058x)} \quad R = 0.98962$

$y = 6.0226 \times e^{(2.8006x)} \quad R = 0.97894$

$y = 4.4667 \times e^{(2.2701x)} \quad R = 0.89064$

$y = 2.0204 \times e^{(2.7708x)} \quad R = 0.91085$

Vant, m/s

37000J/kg

24000J/kg

7000J/kg

5000J/kg

3000J/kg

1000J/kg
\begin{align*}
\text{Core Mass Ratio} & \quad \text{Vant, m/s} \\
37000\text{J/kg} & \quad y = 42.466 \times e^{(11.874x)} \quad R = 0.99618 \\
30000\text{J/kg} & \quad y = 32.668 \times e^{(11.553x)} \quad R = 0.99936 \\
24000\text{J/kg} & \quad y = 24.004 \times e^{(11.661x)} \quad R = 0.99974 \\
16000\text{J/kg} & \quad y = 14.203 \times e^{(11.558x)} \quad R = 0.99977 \\
10000\text{J/kg} & \quad y = 7.563 \times e^{(11.768x)} \quad R = 0.99776 \\
6000\text{J/kg} & \quad y = 3.8874 \times e^{(12.09x)} \quad R = 0.99696 \\
5500\text{J/kg} & \quad y = 3.356 \times e^{(12.342x)} \quad R = 0.9893 \\
3000\text{J/kg} & \quad y = 1.5322 \times e^{(12.09x)} \quad R = 0.98615 \\
2500\text{J/kg} & \quad y = 0.35442 \times e^{(12.373x)} \quad R = 0.96357
\end{align*}
Largest Fragment Mass vs. Energy Density

- **Basalt line**: (Fujiwara and Tsukamoto, 1980)
- **Gypsum line**: (This study; Kawakami et al., 1991)
- **Glass**: (Gault & Wedekind, 1969)

Largest glass fragment mass

Energy Density, J/kg

- Glass target
- Basalt line
- Gypsum line
The energy density for core

Estimation from gypsum line

Estimation from basalt line

Core Mass Ratio

Largest fragment mass, \( \frac{M_l}{M_t} \)

- 400-500 J/kg
- 600-800 J/kg
- 1000-1300 J/kg
- 15000-25000 J/kg
The graph shows a relationship between core mass ratio and energy (in joules per kilogram). The energy levels are categorized into different ranges:

- **400-500 J/kg**
- **600-800 J/kg**
- **1000-1300 J/kg**
- **1500-2500 J/kg**
- **1800-2000 J/kg**
- **2000 J/kg**
- **4000-6000 J/kg**
- **6000 J/kg**
- **7000 J/kg**
- **13000 J/kg**
- **25000 J/kg**

The data points are fitted to exponential functions of the form:

- $y = 0.52391 \cdot e^{-5.6233x}$ with $R = 0.99944$
- $y = 0.42369 \cdot e^{-3.1388x}$ with $R = 0.96666$
- $y = 0.5956 \cdot e^{-2.0968x}$ with $R = 0.95031$
- $y = 0.63393 \cdot e^{-1.3802x}$ with $R = 0.85445$
- $y = 0.96045 \cdot e^{-0.94987x}$ with $R = 0.99181$
- $y = 0.99306 \cdot e^{-0.31508x}$ with $R = 0.80724$

The $R$ value indicates the coefficient of determination, which measures how well the data fits the exponential function.