How to form asteroids from mm-sized grains

*Accepted to A&A   (see poster)

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Objective

Determine how asteroids form out of mm-sized grains.

Vesta (largest asteroid, D ~ 500 km)

Image credit: NASA (Dawn spacecraft, 2011)
How planets form

Overview
- How planets form
- Particle traps
- Aims
- Methods
- Results
- Application

How planets form

Star → Protoplanetary Disk

μm → mm → planetesimals → planets

coagulation → gravity

D ~ 10 – 1000 km
Overview
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- **Particle traps**
- Aims
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Particle traps
streaming instability

Particle size: ~ 1 m

Johansen et al (2009)
Aims

Q: What are the smallest particles that can produce particle clumps?

Q: What are the conditions needed to form particle clumps?
Overview
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Methods

Star

Protoplanetary Disk

Pencil Code
Brandenburg & Dobler (2002)

- Gas: $128^2$ static grid
- Solids: particles
- Box size: $0.2 \, H \times 0.2 \, H$
- Gas mass: $0.5 \, M_{\text{earth}}$
- Solid mass: $0.4 \, M_{\text{moon}}$

around the entire ring
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Methods

\[
\Delta = \frac{V_{kep} - V_{gas}}{C_s}
\]

\[
\tau_f = t_f \Omega_{kep}
\]

\[
Z = \frac{\sum_{solid}}{\sum_{gas} + \sum_{solid}}
\]

Particle scale height \((H_p/H)\)

Simulation time \((t\Omega/2\pi)\)

Sedimentation

Gas removal

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Results

\[ \Delta = 0.05 \]

\[ Z = \frac{\Sigma_{\text{solid}}}{\Sigma_{\text{gas}} + \Sigma_{\text{solid}}} \]

**Overview**
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**at 3 AU**

<table>
<thead>
<tr>
<th>R</th>
<th>0.6 mm</th>
<th>1.9 mm</th>
<th>6 mm</th>
<th>1.9 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau_f )</td>
<td>0.001</td>
<td>0.003</td>
<td>0.01</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Simulation time (t / Orbits)

Solid concentration (Z)

Radial coordinate (x / H)

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Results

Conditions for clumping

\[ \tau_f = t_f \Omega_{\text{kep}} \]

\[ Z = \frac{\sum_{\text{solid}}}{\sum_{\text{gas}} + \sum_{\text{solid}}} \]

![Diagram showing conditions for clumping]

Streaming instability is active
Chondrule aggregates
No clumping
Overview
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Application

$M_{\text{disk}}$, $R_{\text{particle}}$, $Z$ → Asteroid formation region

- No clumping
- Clumping for $R \sim 4 \text{ mm}$
- $\tau_f \gtrsim 0.003$
- $\tau_f \gtrsim 0.006$

- Clumping for $R \sim 1 \text{ mm}$
- $\tau_f \gtrsim 0.003$
- $\tau_f \gtrsim 0.006$

Disk mass ($M_{\text{disk}}/M_{\text{MSN}}$)

Radial distance ($r / \text{AU}$)