Compression at collisions of fluffy dust aggregate

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Abstract

In protoplanetary disks, the planetesimals are formed through the gravitational instability or simple coalescence. Even if the planetesimals are formed through the gravitational instability, dust aggregates must grow up to cm size or so. At such size, dust aggregates would be compressed from their fluffy structure. Such compression changes their cross section and strength.

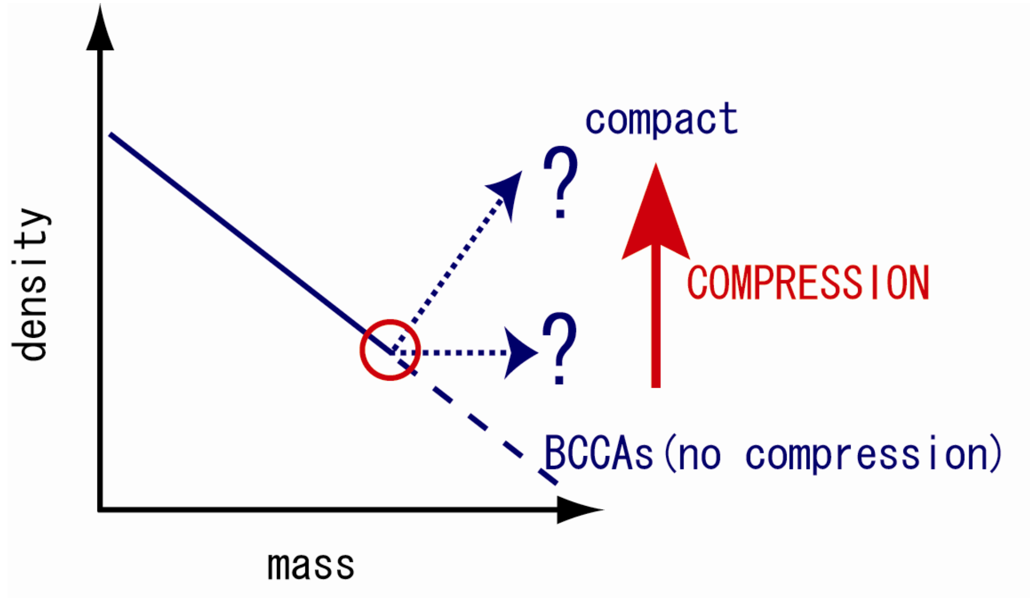
In this study, we perform N-body simulations of dust aggregate collision and examine their compression at collisions. In the simulation, we obtain a resultant aggregate at a collision of two identical aggregates. Using the resultant aggregates, we further perform a simulation of a collision between them. Repeating such simulations of aggregate collision, we examine compression of growing aggregates. In our simulation, the collisional velocity is a parameter. As aggregates grow, the density keeps decreasing at low velocity collisions. On the other hands, at intermediate velocity collisions as aggregates grow, the density decreases to a certain value which depends on the collisional velocity. From our results, we discuss when dust aggregates start to compress in protoplanetary disks.

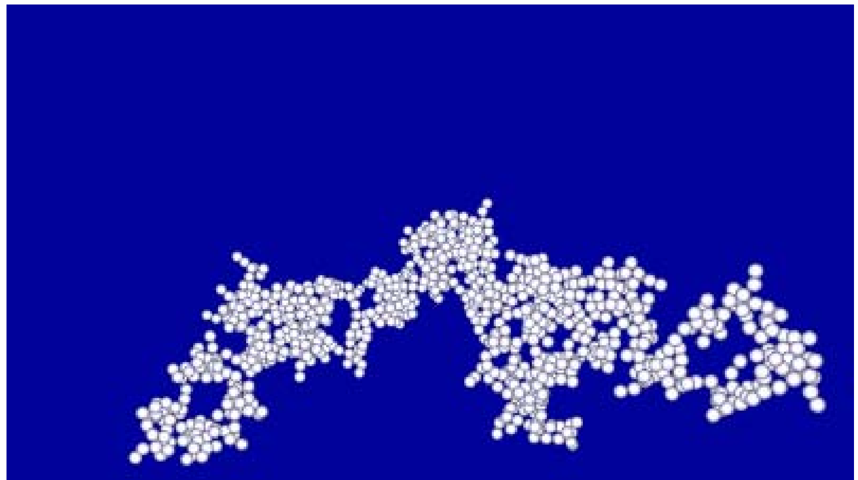
Introduction

- Dust aggregates grow through collisions in protoplanetary disks. Their collisional velocity is determined by the density (or the cross section) of aggregates.

- Dust aggregates would be compressed through collisions and the density increases. If no compression occur, aggregates become BCCAs.

- The manner of compression and the density evolution are governed by the collisional velocity. On the other hand, the increase in the density (and the decrease in the cross section) accelerates the collisional velocity. In this way, the aggregate density evolution is coupled with the collisional velocity.





BCCAs

(Ballistic Cluster-Cluster Aggregates)

Aim in this study

When are aggregates compressed?

How does the density change through collisions?

We perform 3D simulation of aggregate collision with the various collisional velocity. We examine evolution of aggregate density. We also compare our results with the criterion for compression by Dominik and Tielens (1997).

N-body simulation of aggregate collision

- Numerical Procedure
  - Head-on collisions of two identical aggregates (with random orientation)
  - A sequence of aggregate collision: 2 vs. 2 ⇒ 4 vs. 4 ⇒…⇒512 vs. 512
  - We repeat the collisions between two identical aggregates.
  - We perform 50 sequences of collisions for each velocity. We obtain averaged value of connection number, the gyration radii and the densities.

- **Unit:**
  - Length: $r_0=0.1\mu m$; monomer radius
  - Mass: $m_0=4.2\times10^{-18}$ kg ; monomer mass
  - Velocity: $V_0=4.4$m/s

- **Parameter:**
  - Material: Ice
  - Collisional velocity: $\tilde{V}=V/V_0=0.1, 0.5, 1.0$

    For higher velocity cases (V>2.0), fragmentation is dominant.

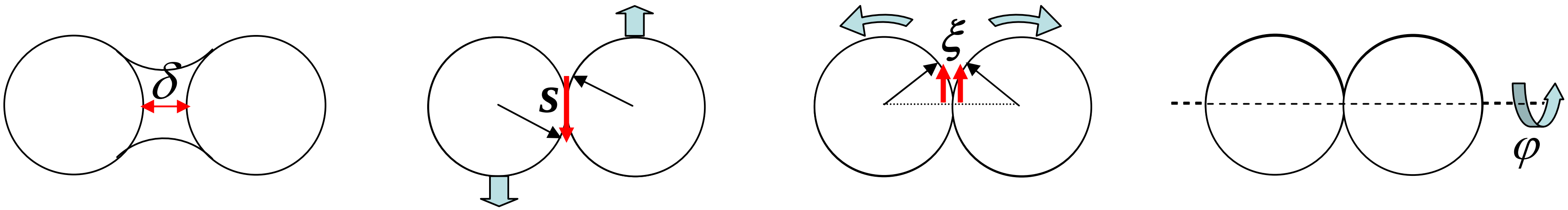
Interaction model

Hertz (1881)
Johnson, Kendall and Roberts (1971)
Johnson (1987), Chokshi et al. (1993)
Dominik and Tielens (1995,96,97)

We calculated the force, using spring-like potentials.

$$U = U_n(\delta) + U_{slide}(s) + U_{roll}(\xi) + U_{twist}(\varphi)$$

Normal | Sliding | rolling | twisting



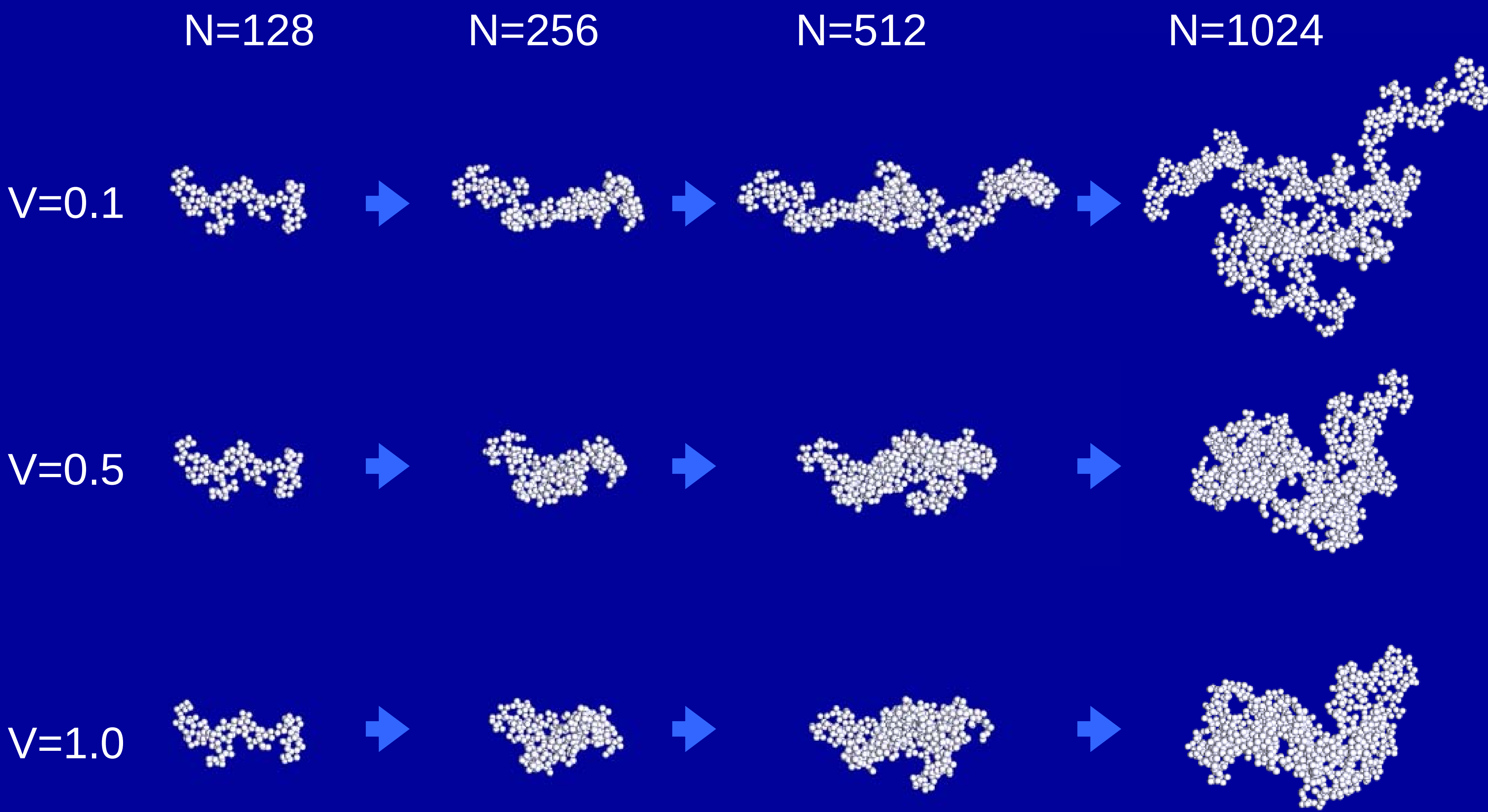
U_n: JKR theory | $U_{slide} = 1/2\, k_s\, s^2$ | $U_{roll} = 1/2\, k_r\, \xi^2$ | $U_{twist} = 1/2\, k_t\, \varphi^2$

k_s k_r k_t : ←elastic constants, surface energy, grain radius

δ, s, ξ, φ > critical displacement ⇒ Energy dissipation

- Critical displacement for slide: $s_{crit} \sim 4.3$Å
- Critical displacement for roll: $\xi_{crit} \sim 30$Å (Heim et al.,1999)
- Critical displacement for twist: $\varphi_{crit} \sim 1^\circ$

Examples of resultant aggregates



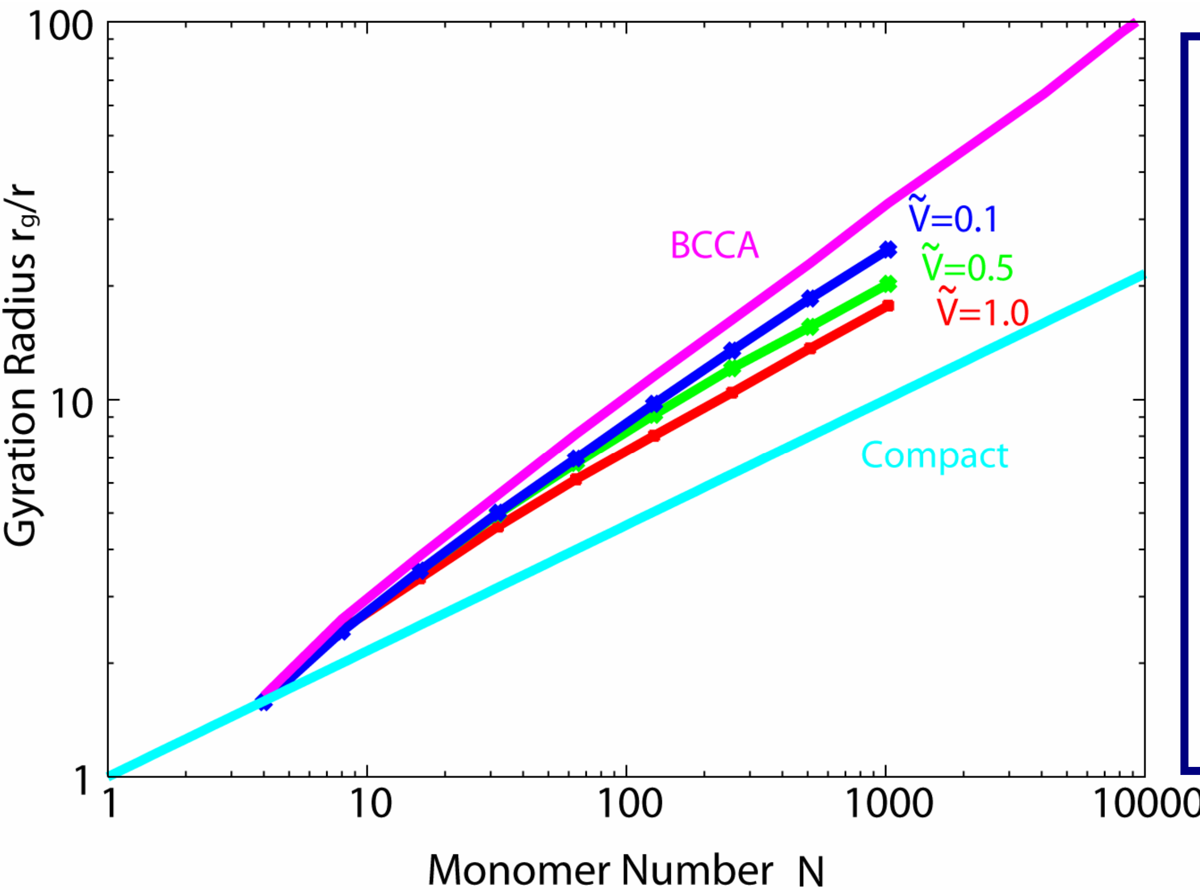
Gyration radius of aggregates

Definition:

$$r_g = \sqrt{\frac{\sum_{i=1}^{N} (x_i - x_g)^2}{N}}$$

- BCCAs (Head-on) : $r_g/r_0 \sim N^{1/2}$
- compact aggregates : $r_g/r_0 \sim N^{1/3}$

Each point is obtained from the average of 50 runs.

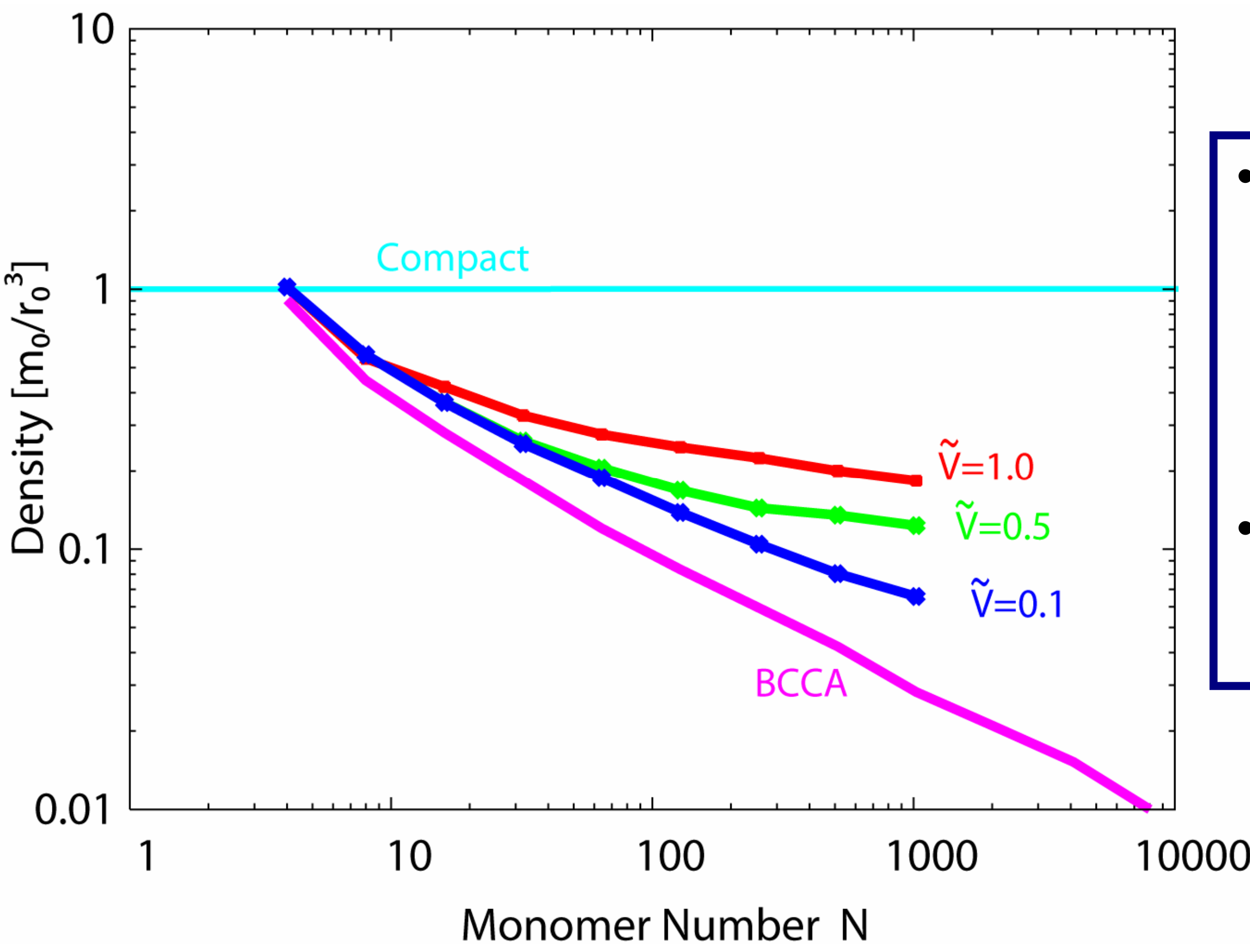


- As aggregates grow, they deviate from BCCA line. That is, they are gradually "compressed".
- As collisional velocity is higher, compression occurs earlier and strongly.
- However, the compression stops before aggregates become completely compact.

Density of aggregates

We estimate aggregate density, assuming $\rho \sim mN/r_g^3$.

- BCCAs : $\rho \sim N^{-1/2}$
- compact aggregates : ρ =constant



- At intermediate velocity cases (V=0.5, 1.0) as aggregates grow, the density decreases, the density becomes almost constant.
- At the case of V=1.0, the density is expected to attain to a lower limit at larger N.

Criterion for compression

According to Dominik & Tielens (1997), the beginning of compression is estimated by

$$\frac{1}{2} m_0 N_{crit} V^2 = E_{roll}$$

$$\Rightarrow \boxed{N_{crit} = \frac{2E_{roll}}{m_0} V^{-2} = 22 \tilde{V}^{-2}}$$

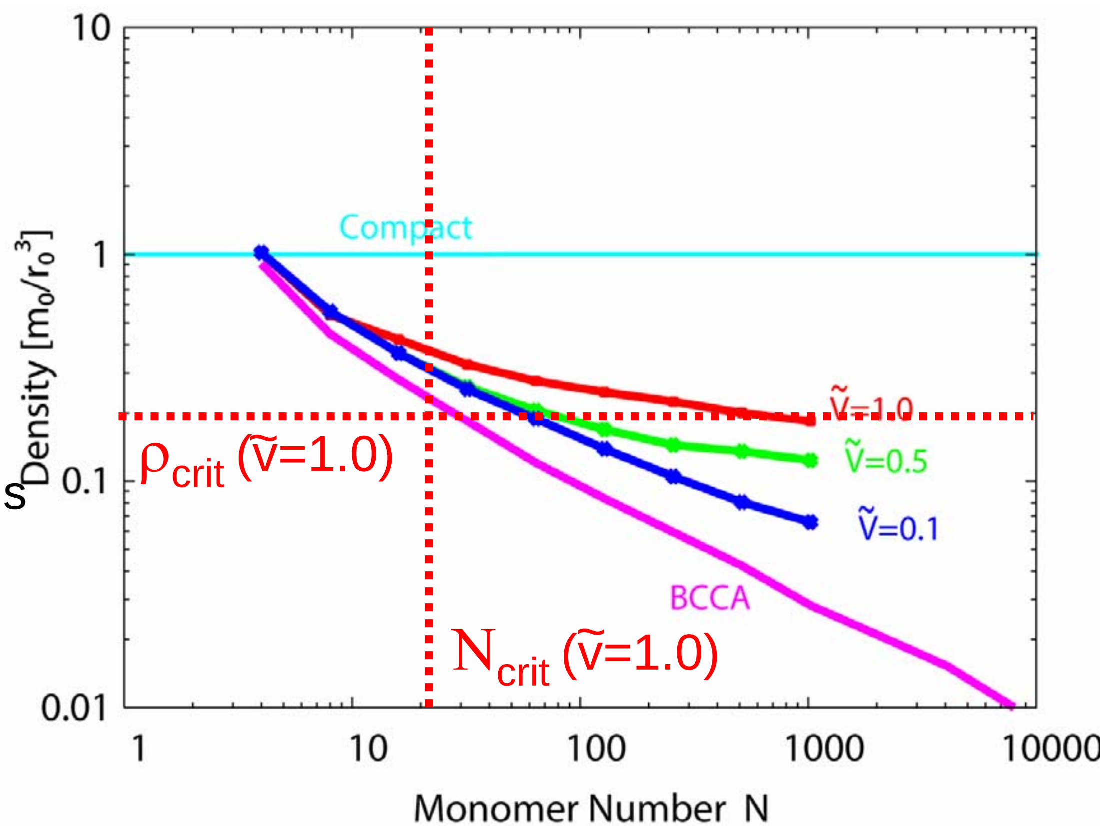
On the other hand,

$$\begin{cases} r_g \sim N^{\frac{1}{2}} r_0 \ \text{(BCCA)} \\ \rho \sim \dfrac{m_0 N}{r_g^3} \end{cases}$$

Then the critical density ρ_{crit} for compression is estimated to be

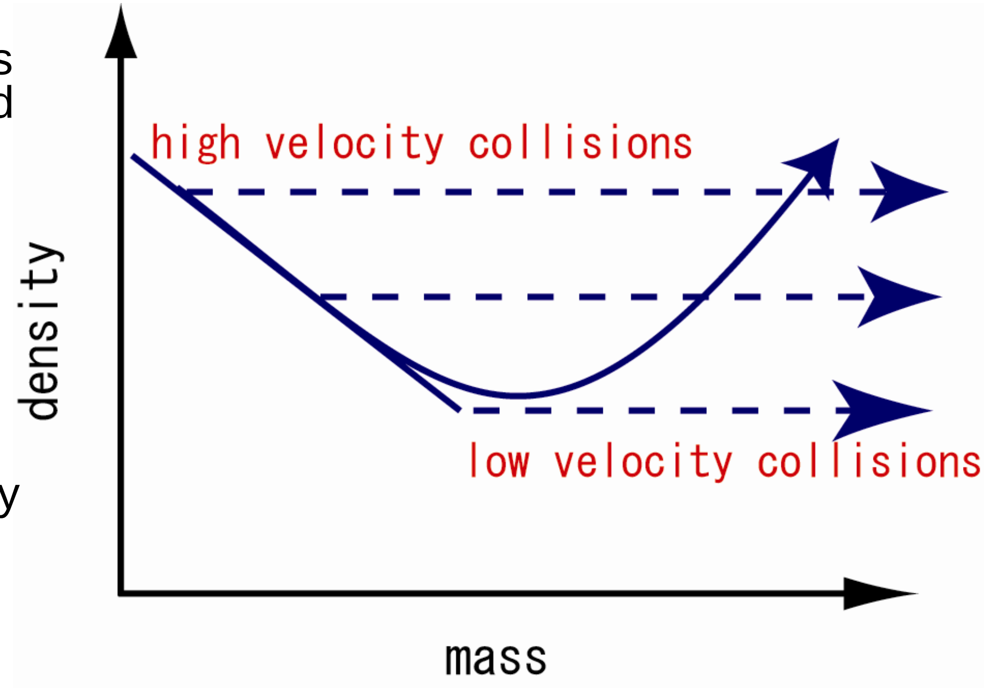
$$\boxed{\rho_{crit} = N^{-\frac{1}{2}} \frac{m_0}{r_0^3} = 0.21 \tilde{V} \, [m_0 / r_0^3]}$$

Our numerical results are almost consistent with this estimation. In order to check the consistency between them more precisely, we needs further numerical simulations.



Implication ~ coupling of the collisional velocity with the density~

- In protoplanetary disks, the collisional velocity is governed by the gas drag force. It is determined by m/S. For BCCAs, m/S is constant through the growth.
- As aggregates grow, their density attains to the lower limit which depends on the collisional velocity.
- Once we obtain the relation between the density and the collisional velocity, we can discuss in more realistic cases where the collisional velocity depends on m/S.
- In our simulations, the critical density increases with the collisional velocity. However, we can not clarify the velocity-dependence, because we only performed simulations of collisions between small aggregates.
- We will perform simulations of the low velocity collisions between large aggregates to clarify the relation the density and the collisional velocity.



compression

↓

As the ratio (m/S) decreases,
the velocity increases.

↓

$\rho_{crit}(V)$ also increases

Summary

- We performed N-body simulations of dust aggregates collisions.
- We obtained the gyration radius, the connection number and the density in the course of compression of aggregates.
- As aggregates grow, the density becomes a critical value ρ_{crit}. Our simulations are consistent with the critetion for compression by Dominik & Tielens 1997.
- We will perform simulations of the low velocity collisions between large aggregates to clarify the relation the density and the collisional velocity.