# Direct $N$–body simulations of rubble pile collisions in strong tidal fields: Applications to Saturn's F ring

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## Abstract

We present $N$-body simulations of planetesimal collisions and accretion in a strong tidal field modeled after the environment of Saturn's F ring. These simulations examined the outcome of collisions between gravitational aggregates, or rubble piles, with the collision speed, mass ratio and coefficient of restitution being the variable parameters. The outcomes proved to be very dependent on collision speed and the coefficient of restitution, and less dependent on mass ratio. These results demonstrate a complicated collisional environment for icy bodies in planetary rings, and shed light on important assumptions made in previous models, most importantly those of complete accretion.

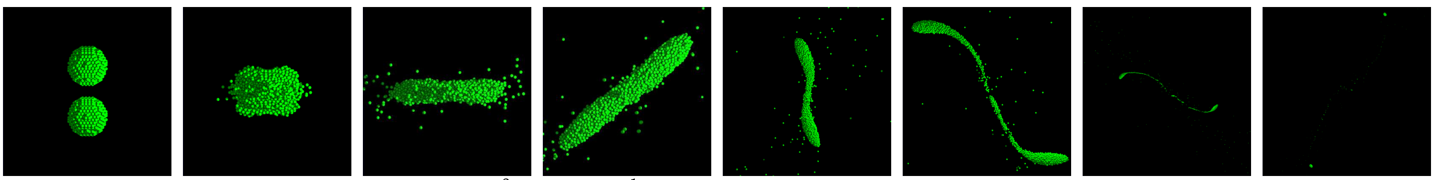

FIGURE 1: Equal mass bodies with a bulk density of 1.0 g cm$^{-3}$ colliding at 5 m s$^{-1}$ with a coefficient of restitution 0.5 in orbit around a Saturn–mass central object at the distance of Saturn's F ring.

## Rubble Pile Collisions

- Evidence for rubble piles found in:
  - spin period analysis
  - crater chains
  - tidal breakups
  - density/porosity measurements
- Rubble pile collisions previously modeled by Leinhardt & Richardson 2002 to explore effects of mass ratio, impact speed, impact parameter and coefficient of restitution on collision outcome.
- Analytical estimates for colliding rubble piles consider rubble pile's mutual Hill Sphere, impact speed and coefficient of restitution to determine results in a tidal field (Canup & Esposito 1995).

## Saturn's F ring

- Located at 2.32 R$_♄$, Saturn's F ring is just beyond the classical Roche limit for 1 g cm$^{-3}$ density bodies.
- Shepherding by moons Prometheus and Pandora causes stable sturctures.
- Brightness variations, braided strands and bright burst events have been observed.
- Meterorite impact model (Showalter 1998) and moonlet collisions model (Barbara & Esposito 2002) attempt to explain short lived prominent burst events.
- Previously modeled analytically with rubble pile (moonlet) collisions using mass ratio limit (100:1) as cutoff for complete accretion (Barbara & Esposito 2002).

## Planetesimal Model

- Rubble Piles
  - identical 100 m diameter particles
  - bulk density of 1.0 or 0.5 g cm$^{-3}$
  - ∼ 50, 500, 1200 and 5000 particle piles
- Coefficient of restitution
  - normal coefficients ($\epsilon_n$) were 0.5 and 0.8
- Collisions
  - all take place at 2.32 R$_♄$ from Saturn
  - impact speeds between 1 and 10 m s$^{-1}$
  - impact parameter $q$ always 0.0 (head-on collisions)

## Parameter space

### Mass ratio experiments

- Three mass ratios examined at three velocities for two bulk densities and coefficients of restitution.
  - Mass ratios 1:1, 1:10, 1:100
  - Velocities 1, 5 and 10 m s$^{-1}$
  - Bulk densities 0.5 and 1.0 g cm$^{-3}$
  - $\epsilon_n$ = 0.8 and 0.5

### High resolution experiments

- Equal mass bodies studied at intermediate velocites 1 to 10 m s$^{-1}$ at higher resolution, 1200 particles.

## Results

### Mass ratio

- Nearly complete accretion for 1 m s$^{-1}$ cases.
- Intermediate mass ratio (10:1) depends strongly on bulk density.
- High impact speed cases (10 m s$^{-1}$) had mild to no accretion for the 100:1 mass ratio, and are less dependent on bulk density.

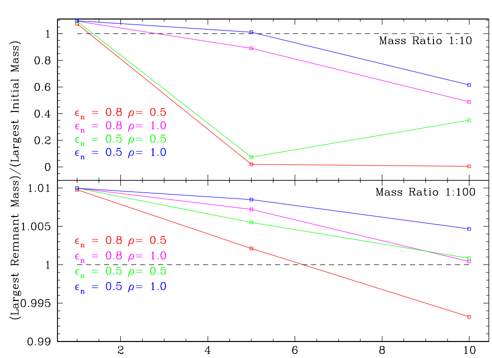


FIGURE 2: Amount of accretion as a function of impact speed for the four cases of bulk density and coefficient of restitution and two separate mass ratios. On the plot values greater than 1.0 represent accretion while values less than 1.0 represent erosion.

### High resolution

- Very sharp cutoff between accretion and disruption.
- Lower bulk density (0.5 g cm$^{-3}$) cases accrete only for 1 m s$^{-1}$.
- No accretion for any cases above 4 m s$^{-1}$.

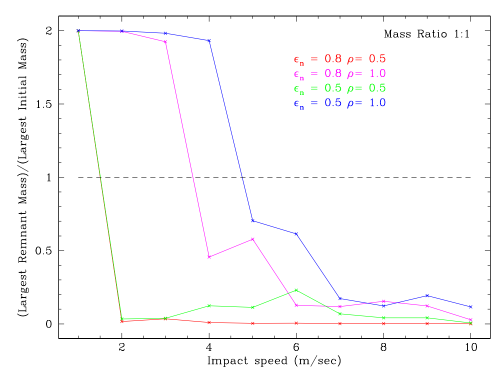


FIGURE 3: High-resolution equal-mass collision accretion values as a function of impact speed for the four cases of bulk density and coefficient of restitution. The plot shows the sharp cutoff between accretion and erosion as a function of velocity.

## Conclusions

- Complete accretion (100 % of impactor) is rare, even at low velocity, for all tested cases.
- Equal mass bodies can accrete in the regime of Saturn's F ring, but there is a sharp velocity cutoff.
- Large mass ratio cases (1:100) lead to erosion for some high velocity collisions.

## References

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Leinhardt, Z. M. & Richardson, D. C. 2002, Icarus, 159, 306–313.
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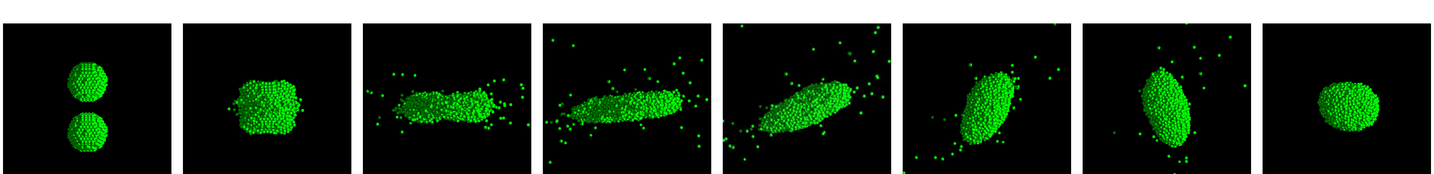

FIGURE 4: Equal mass bodies with a coefficient of restitution 0.5 and a bulk density of 1.0 g cm$^{-3}$ colliding at 4 m s$^{-1}$ in orbit around Saturn.

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