Observing Planet Formation: The Impact of Collisions

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Snapshots from Observations

Hubble Space Telescope Orion Nebula Proplyd Atlas 2009
Snapshots from Observations
This is the process that we would like to understand. It is effectively invisible.
Planetesimal Collision Outcomes

Planetesimals in the gravity regime > 1km
Evolution code: PKDGRAV (N-body)
Collision model: EDACM
Empirically Derived Analytic Collision Model (EDACM)

\[ Q_{RD}^* = q_s \left( \frac{S}{\rho_1} \right)^{3\mu/(\phi+3)/(2\phi+3)} R_{C1}^{9\mu/(3-2\phi)} V^*(2-3\mu) + q_g \left( \frac{\rho_1 G}{\phi+3} \right)^{3\mu/2} R_{C1}^{3\mu} V^*(2-3\mu) \]

Strength Regime

Gravity Regime

Material specific parameter

(Benz & Asphaug '99)

Coupling parameter ~ 0.35
momentum scaling

Leinhardt & Stewart 2009, Leinhardt et al. 2000
Leinhardt & Stewart 2012
A. Collision parameters

Specific impact energy

\[ Q_R = \left( \frac{\alpha M_p M_t}{(\alpha M_p + M_t)} \right) \frac{V_i^2}{2(\alpha M_p + M_t)} \]

B. Catastrophic disruption criteria

\[ Q_{RD}^* = \mathcal{F} \left( c^*, M_{tot}, M_p / M_t, \theta, V^*, \bar{\mu} \right) \]

C. Mass of the largest remnant

\[ M_{lr} / M_{tot} = \mathcal{F} \left( Q_R / Q_{RD}^* , \eta \right) \]

D. Maps of collision outcomes

Leinhardt & Stewart (2012)
Numerical Method: Quiet Terrestrial Planet Formation

1. **Evolution code**: N-body gravity code PKDGRAV

2. **Collision Model**: a) perfect merging; b) RUBBLE; c) EDACM

3. **Planetesimal disk**: Standard surface density (MMSN) 
   \[ \Sigma = \Sigma_1 \left( \frac{a}{1\text{AU}} \right)^{-1.5}, \Sigma_1 = 10 \text{ g/cm}^2 \]
   
   \[0.5 < a < 1.5 \text{ AU}\]
   
   \[N_{\text{init}} = 10^4, \ R \sim 100 \text{ km}, \ f = 6\]
   
   No gas
Results: Formation of Embryos

Leinhardt et al. in press
Results: Degree of Planetesimal Mixing

Embryo Composition at 400,000 yr (14.4 Myr)

- Each colour shows amount (% mass) of material both resolved and unresolved accreted from a particular semi-major axis

- Both RUBBLE and EDACM show limited mixing

Leinhardt et al. in press
Results: Planetesimal Collision Outcomes

Leinhardt et al. in press
Results: Instantaneous Dust Images

Quiet runaway and oligarchic growth not observationally visible with ALMA
But what if the scenario is not quiet? What if there is a perturber?

Leinhardt et al. in press
Transitional (& Pre-transitional) Disks

- MWC 758: Grady et al. 2013
- PDS 70, pre-transitional disk: Hashimoto et al. 2012
- SAO 206462: Muto et al. 2012
- LkCa 15 disk: Kraus & Ireland 2012
Numerical Method: Quiet Terrestrial Planet Formation

1. **Evolution code:**
   N-body gravity code PKDGRAV

2. **Collision Model:**
   EDACM+

3. **Planetesimal disk:**
   Standard surface density (MMSN)
   \[ \Sigma = \Sigma_1 (a/1\text{AU})^{-1.5}, \Sigma_1 = 10 \text{ g/cm}^2 \]
   \[ 0.5 < a < 10 \text{ AU} \]
   \[ N_{\text{init}} = 10^6, R \sim 100 \text{ km}, f = 1 \]
   Gas, Jupiter-mass planet @ 2.8 AU

Bluecrystal Supercomputer UoB
Numerical Method: EDACM+

Resolved Rubble-pile Collision

EDACM+

\[ M_p/M_t = 0.25 \]

\[ v = 50 \text{ m/s}, \ b = 0.9 \]
\[ v = 38 \text{ m/s}, \ b = 0.0 \]

Leinhardt et al. in press
Results: Collisional Stirring from a Circular Planet

Dobinson, Leinhardt et al. in prep.
Results: Planetesimal Collision Outcomes

- No Planet (control)
- Circular Planet
- Eccentric Planet (e=0.1)
- Eccentric Planet (e=0.2)

Dobinson, Leinhardt et al. in prep.
Results: Collisional Stirring from an Eccentric Planet

Dobinson, Leinhardt et al. in prep.
Conclusions & Caveats

• Our current work suggests it will be hard to observe planetesimal evolution if the growth environment is dynamically quiet

• A more active environment such as an embedded planet increases dynamical temperature will result in more debris

• No primordial dust - needed to create most realistic synthetic images - working on it

• In transitional disk work - just one planet - wide gap transitional disks would require more than one

• Location of the planet picked to make simulations numerically practical - not at observed location of gaps