The dynamical evolution of transiting planetary systems including a realistic collision prescription

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The *Kepler* Dichotomy: an excess of systems with a single transiting candidate

Johansen *et al.* 2012; see also Fang & Margot 2012, Ballard & Johnson 2016
The *Kepler* Dichotomy: explanations
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“Grinding down”

- Unstable non-resonant systems (Pu & Wu 2015, Volk & Gladman 2015)
- Unstable resonant systems (Izidoro *et al.* 2017)
- Secular resonance sweeping (Spalding & Batygin 2016)
- Destabilisation by outer systems (Mustill *et al.* 2017, Huang *et al.* 2017)
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- *In situ* embryo accretion (Hansen & Murray 2013, Moriarty & Ballard 2016)
- Other formation effects (number of cores/seeds, &c.)
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Collisions
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What are the encounter velocities in unstable planetary systems?

\[ v_\infty = \sqrt{GM_\star (1 + e_2) / a_1} - \sqrt{GM_\star / a_1} \]

Pericentre velocity of outer planet

Keplerian velocity of inner planet

This is a minimum: will be higher including \( z \)-components of velocity and gravitational focusing.
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\[ v_\infty = \sqrt{GM_\star (1 + e_2)} / a_1 - \sqrt{GM_\star} / a_1 \]

Pericentre velocity of outer planet
Keplerian velocity of inner planet

\[ v_{\text{coll}} / v_{\text{esc}} \] sets how destructive the collision is.
Improving the collision treatment in the MERCURY $N$-body integrator
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  - Low collision velocity: retain perfect merging.
  - Large impact parameter, moderate velocity: hit-and-run impact. Geometrical approximation for mass “shaved off”.
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• Improve the algorithm for resolving collisions:
  • **Low collision velocity:** retain perfect merging.
  • **Large impact parameter, moderate velocity:** hit-and-run impact. Geometrical approximation for mass “shaved off”.
  • **High velocity:** disruptive or super-catastrophic impact. Scaling laws from Leinhardt & Stewart (2012). Modifications to allow for disparate densities.

• Treatment of collision fragments: two approximations:
  • **Instantaneous removal:** mass lost in collision is removed from integration. Represents mass lost as small grains, removed by radiation forces
  • **Full retention:** mass is distributed into super-particles. Fragment velocity distribution from Jackson & Wyatt (2012), scaled to planetary escape velocity. Represents mass lost as larger chunks.
Improving the collision treatment in the MERCURY N-body integrator

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Use this as most extreme case
Begin

Small body hits big body?

- Yes: Perfect merging
  - Yes: Supercatastrophic disruption
  - No: Disruptive impact
    - Yes: Hit-and-run collision
    - No: Regular disruption

- No: Disruptive impact
  - Yes: Head-on impact
    - Yes: Grazing impact
    - No: Disruptive impact
      - Yes: Regular disruption
      - No: Regular disruption

$v_{\text{coll}} < v'_{\text{esc}}$?

$b < b_{\text{crit}}$?
Collision outcomes in unstable super-Earth systems
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Collision outcomes as function of inner planet's semimajor axes

Decreasing $v_{\text{Kep}}$, constant $v_{\text{esc}}$

- Perfect merger
- Imperfect accretion
- Erosion
Collision outcomes in unstable super-Earth systems

Collision outcomes as function of inner planet's semimajor axes

Collision outcomes as function of planetary mass range

Decreasing $v_{\text{Kep}}$, constant $v_{\text{esc}}$

Increasing $v_{\text{esc}}$, constant $v_{\text{Kep}}$
Collision outcomes in unstable super-Earth systems

Collision outcomes as function of planetary mass range
- Increasing $v_{\text{esc}}$, constant $v_{\text{Kep}}$
- Perfect merger
- Imperfect accretion
- Erosion

Collision outcomes as function of inner planet's semimajor axes
- Decreasing $v_{\text{Kep}}$, constant $v_{\text{esc}}$
- Perfect merger
- Imperfect accretion
- Erosion

Collision outcomes as function of mutual Hill radii
- Constant $v_{\text{Kep}}$, constant $v_{\text{esc}}$
- Perfect merger
- Imperfect accretion
- Erosion
Collision outcomes in unstable super-Earth systems

Collision outcomes as function of inner planet's semimajor axes

- Perfect merger
- Imperfect accretion
- Erosion

Collision outcomes as function of planetary mass range

- Perfect merger
- Imperfect accretion
- Erosion

Collision outcomes as function of mutual Hill radii

- Perfect merger
- Imperfect accretion
- Erosion

Collision outcomes as function of system configuration

- Perfect merger
- Imperfect accretion
- Erosion

Decreasing $v_{\text{Kep}}$, constant $v_{\text{esc}}$

Increasing $v_{\text{esc}}$, constant $v_{\text{Kep}}$

Constant $v_{\text{Kep}}$, constant $v_{\text{esc}}$

Stronger eccentricity excitation
At 0.1 au most collisions are not perfect mergers. But erosive collisions do not result in much mass loss.
Little impact on final multiplicity after instability

Hard to grind a system down to one or zero detectable planets

Alexander Mustill — PLATO Mission Conference 2017-09-07
Exception: when starting from smaller planets
**Observed multiplicities: still not enough singles**

- Observed multiplicities: around 6 singles for every 1 double (depending slightly on selection criteria), *e.g.* Johansen *et al* (2012), Lissauer *et al* (2014)
- Our unstable multiples reduce to ~3:1 observed singles:doubles
- Still need extra source of singles (see also Izidoro *et al* 2017 for initially resonant systems, perfect merging assumed)
Effects on *in-situ* formation from embryos

Always perfect merging: high-multiplicity systems formed

Realistic collision algorithm: few high multiplicity, many singles and zeros

Caveat: fragments removed (no reaccretion)
Conclusions

- Collisions between planets or embryos at \(~0.1\) au usually do not result in perfect mergers.

- Fewer perfect mergers when planets are smaller, or high eccentricities are excited by outer system dynamics.

- Many collisions are grazing impacts resulting in little mass loss.

- Little effect on final mass distribution or multiplicity when starting from large planets.

- In-situ formation from embryos is strongly affected by the collision prescription. If collision debris is efficiently removed, many single- or zero-planet systems form. Contribution to the Kepler dichotomy for rocky planets.

- See arxiv.org/abs/1708.08939 for further details.
At small orbital distances, Keplerian velocity can significantly exceed surface escape velocity.
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Final mass distributions in unstable super-Earth systems

KS $p = 0.168218$, $N_I = 203$, $N_r = 196$
Abandoning the perfect merging algorithm results in more widely-spaced systems.

Empirical *Kepler* distribution
(Weiss *et al* 2017)