How an Early Instability Shapes the Inner and Outer Solar System

M.S. Clement and N.A. Kaib (in prep)
Motivation

• An EARLY Instability:
  – Timing of instability dependent on initial disk properties (Gomes et al, 2005).
  – Difficult for terrestrial planets to survive a late instability (Brasser et al, 2009, Kaib & Chambers, 2016).
  – Projectile size distribution for a late instability different than observed (Morbidelli et al, 2017).
  – Self Interacting Disks unlikely to last 400 Myr (Quarles & Kaib, in prep).

Fassett and Minton (2012)
Mars Mass Deficit Problem

- Mars analogues are rare in embryo accretion models, Mercurys are almost non-existent.

- Possible Solutions:
  - Extra Eccentric Jupiter and Saturn (Raymond, 2009)
  - 0.7-1.0 AU annulus (Hansen, 2009)
  - Grand Tack Model (Walsh et al, 2011)
  - Local Depletion (Izidoro et al, 2015)
How would an early instability affect the forming Terrestrial Planets?

- Integrate a resonant configuration of Giant Planets right up to the instability:

- Evolve the terrestrial planets, take snapshots of the system at $10^4, 10^5, 10^6$ and $10^7$ yrs:

- Imbed the forming terrestrial planets in the instability and integrate for 200 Myr:
Simulation Parameters

- Mercury6 Hybrid Integrator, 6.0 day time-step (Chambers, 1999).
- Inner Disk: 100 embryos/1000 planetesimals/ $r^{-3/2}$ surface density profile:

<table>
<thead>
<tr>
<th>Run Number</th>
<th>Disc Mass ($M_\oplus$)</th>
<th>Disc Inner edge (AU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-24</td>
<td>5.0</td>
<td>0.5</td>
</tr>
<tr>
<td>25-49</td>
<td>5.0</td>
<td>0.7</td>
</tr>
<tr>
<td>50-74</td>
<td>3.0</td>
<td>0.5</td>
</tr>
<tr>
<td>75-99</td>
<td>3.0</td>
<td>0.7</td>
</tr>
</tbody>
</table>

- Outer Disk: 1000 bodies/ $r^{-1}$ surface density profile (Nesvorny & Morbidelli, 2012):

<table>
<thead>
<tr>
<th>Name</th>
<th>$N_{Pln}$</th>
<th>$M_{disc}$ ($M_\oplus$)</th>
<th>$\delta r$ (AU)</th>
<th>$r_{out}$ (AU)</th>
<th>$a_{nep}$ (AU)</th>
<th>Resonance Chain</th>
<th>$M_{ice}$ ($M_\oplus$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>n1</td>
<td>5</td>
<td>35</td>
<td>1.5</td>
<td>30</td>
<td>17.4</td>
<td>3:2,3:2,3:2,3:2,3:2:2</td>
<td>16,16,16</td>
</tr>
<tr>
<td>n2</td>
<td>6</td>
<td>20</td>
<td>1.0</td>
<td>30</td>
<td>20.6</td>
<td>3:2,4:3,3:2,3:2,3:2,3:2</td>
<td>8,8,16,16</td>
</tr>
</tbody>
</table>
Results

• 69.5% of all Mars analogues formed small.
• 46.8% of systems form no Mars (84% no or small).
• Most successful when instability is delayed 10 Myr in to terrestrial planetary formation:
  – 20% correct architecture of inner planets (28% when S:J<2.8).
  – 26% correct mass ratios of inner planets (42%).
  – 11% form Mars in less than 15 Myr (28%).
  – 66% form Earth in greater than 50 Myr (85%).
  – 39% leave behind an Asteroid Belt with no embryos (40%).
  – 22% AMD < .0036 (44%)
Mars’s Formed

![Cumulative Fraction vs Mass (M⊕) graph]
Mars’s Formed
Planets Formed
Planets Formed

![Graphs showing the relationship between semi-major axis and mass for Planets Formed. The graphs compare data between 1e6 and 1e7.]
Water Delivery
Water Delivery

![Graph showing water delivery percentages across different semi-major axes.](image)
Earliest Instabilities and Collisional Fragmentation

- The earliest instabilities we look at often look nothing like the solar system:
  - No Mars.
  - Only one planet.
  - All planets too small.
- System’s with the most violent instabilities are most likely to finish with a few small, or no terrestrial planets.
- Collisional Fragmentation can play a large role in embryo accretion and must be accounted for (Chambers, 2013).
- Collisional velocities in our runs are LOW for Earth and Mars analogues and HIGH for Venus analogues.
Summary

• An early instability can have a large effect on terrestrial planetary formation.
• Significantly REDUCES the MASS of MARS ANALOGUES.
• When the instability occurs ~1-10 Myr into the giant impact phase:
  – Mars is left as a stranded embryo.
  – Significant amount of material from > 2 AU is scattered towards the forming Earth.