The New Dynamics of Solar System Formation

Hal Levison
Southwest Research Institute
Boulder, CO
USA

An Apple- and Microsoft-Free Presentation
The ‘Standard’ $6^{1/2}$ Steps of Planet Formation in the Solar System

- **Step 0.5**: The disk forms dust settles to a the mid-plane.
- **Step I**: Planetesimal Formation.
  - Particles concentrate due to turbulence $\implies$ gravitational instabilities. (Cuzzi et al.; Johansen et al.)
- **Step II**: Runaway Growth (Greenberg et al.; Wetherill & Stewart)
  \[
  \dot{M} \propto \sigma \propto R^2 \left[1 + \left(\frac{v_{esc}}{v_{rel}}\right)^2\right] \\
  \implies \dot{M} \propto R^4 \propto M^{4/3}.
  \]
- **Step III**: Oligarchic Growth (Kokubo & Ida; Thommes et al.; Chambers)
  - Stirring causes $v_{esc}/v_{rel}$ is $\sim$ constant with mass, so $\dot{M} \propto M^{2/3}$.
  - So, smaller oligarchs can catch up with larger ones.
- **Step IV**: Late Stage (Chambers & Wetherill; Agnor et al.; O’Brien et al.)
  - Violent endgame for terrestrial planets $\implies$ much mixing.
- **Step V**: Gas Accretion (Mizuno)
  - Time of Grand Tack. (Walsh et al.)
- **Step VI**: Instabilities (Thommes et al.; Tsiganis et al.)
  - Time of Nice model. (Gomes et al.)
Step IV:

**Late Stage**

- Oligarchic growth ends when damping (via small guys) is too week to keep the big guys well behaved.
- Embryos scatter each other $\implies$ all hell breaks lose.  
  \[\text{(O’Brien, Morbidelli, & Levison 2006)}\]

- Widespread radial mixing over the entire inner Solar System.
- **Terrestrial planets in Solar System:**  \(\text{(Chambers & Wetherill; Raymond et al.)}\)
  - Usually get 2 or 3 big planets and some little guys.
  - However, Mars is tooooooo big.  
  - Takes between $\sim 30$ and $\sim 200$ Myr.
**An Aside: Asteroid Belt Formation and the Origin of Earth’s Water**

- The asteroid belt:
  - is dynamically excited ($e_{RMS} = 0.15$).
  - is depleted by a factor of $\sim 1000$. ☑

- Wetherill suggested that planets began to form, but were removed by Jupiter resonances. ☑
  - This predicts the correct mass depletion.
  - It produces an excited belt (with bad statistics).

- Morbidelli et al. shows that this can bring in a lot of water.
  - Asteroids from outer asteroid belt are 10% water by mass.
  - Comes in after the Earth is almost fully formed.

**But**, it now looks like the AB never contained embryo-mass objects.

- The asteroid belt needed to be very massive for embryos to form.
  - But this is inconsistent with the survivability of Vesta. *(Bottke et al.)*

- Embryos did not excite the asteroid belt. *(Minton et al.)*
  - The eccentricity distribution is too smooth. ☑ ☑
  - Inclinations are too small if embryos removed 99% of the belt.
    *(Obs $\sim 20^\circ$, Model $\sim 35^\circ$)*

In addition, the assumption that the inner planetary system was dry seems to be incompatible with earlier stages.
From Weidenschilling (1977)
A Complication: Gas-Driven Planet Migration
Gravitational interaction between a growing planet and gas disk causes the planets to move. (Goldreich & Tremaine; Ward)

- Two basic types are often invoked:
  - **Type I**
    - Planet is too small to affect the global $\Sigma$ of the disk.
    - **Problem**: Planet migrates faster than it can grow.
    - Planets fall into the Sun?
    - So, why are the terrestrial planets so very dry ($\ll 1\%$).
  - **Type II**
    - Planet opens a gap.
    - This is probably responsible for the plethora of large planets close to their stars.
    - **Problem**: Why is there is no hot Jupiter here?

I address each of the problems separately.
**Planetesimal-Driven Migration**

- Planets will migrate when placed in a disk of planetesimals.
  - First seen by Fernandez and Ip for Uranus and Neptune. (although see Levison et al. 2010)
  - Assumed unimportant during formation.

- Time-scales:
  - **Type I**: \( t_I \sim 8 \times 10^5 \left( \frac{M_{\text{em}}}{1M_\oplus} \right)^{-1} \left( \frac{\Sigma_{\text{gas}}}{\Sigma_{\text{MMSN}}} \right)^{-1} \left( \frac{a}{5 \text{ AU}} \right) \text{ yr} \) (Tanaka et al. 2002)
  - **P-D**: \( t_p \sim 10^5 \left( \frac{\Sigma_{\text{solid}}}{\Sigma_{\text{solid, MMSN}}} \right)^{-1} \left( \frac{a}{5 \text{ AU}} \right) \text{ yr} \) (Ida et al. 2000; Kirsh et al. 2009)
  - For a solar metalicity disk \( t_p < t_I \) if planet is less than \( 8 M_\oplus \).

- When both are included in \( N \)-body simulations, Planetesimal-driven migration usually wins!

- So, I think we really don’t have to worry about Type I anymore.
  - And it turns out that planetesimal-driven migration can do some wonderful things.
Planetesimal-Driven Migration: The Case for Mars
(Minton & Levison 2011+)

- Current terrestrial planet formation simulations cannot make Mars.
  - It is toooooooo small.
- But they assume:
  1. That all embryos form at the same time.
  2. A MMSN (i.e. they ignore collisional grinding, which is important).

We developed a new code to study accretion:
- Embryos really grow from the inside out.
- Occasionally, one gets lucky and can migrate.
- Happens a few times in each SS.
- Embryo takes off $\implies$ Grows like mad.
- Is Mars-mass when it get to 1.5 AU.
- Outer regions get excited enough for the planetesimals to grind.

Naturally explains Mars’s mass, chemical differences (if any), and old age.
Simulated Mars analogues

Actual Mars

From: Raymond et al. 2009

Semimajor Axis (AU)

Mass (Earth masses)
Planetary Mass

Time (Myr)

Mass (Earth-mass)

Outer Embryo

Embryo @ 1.3AU

a > 1.2 AU
An EXTREME Case of Planetesimal-Driven Migration

- Mars stopped before because we truncated the disk at 1.5 AU.
- This is what happens when we do not do that:
  - We get large embryos (giant planet cores?) at $a > 5$ AU.
  - Takes less time than growing something at 5 AU.
  - Indeed, it solves a long-standing timescale problem.

We are looking at whether all the giant planets could form this way:
- The inner Solar System spits one out at a time.
- Neptune is the oldest planet in the Solar System.
- Jupiter forms just as the gas is going away.
  - Predicts (?) that Jupiter will have the smallest core.
- Mars stalled because the gas was no longer there.
Why isn’t Jupiter sitting next to the Sun?

- Migration stops if Jupiter and Saturn are in the 2:3 MMR. 

(Masset & Snellgrove 2001)

- Walsh et al. argue that:
  - Jupiter started to migrate in.
  - Saturn was in its 2:3 MMR.
  - When Jupiter was ≲ 2 AU, Saturn grew large enough to open gap.
  - Gas flows by planets.
  - They migrate out.

- This can explain the AB low mass and dynamical state.
  - And may supply another way to make Mars. *(See Nader’s talk)*

- It also delivers icy objects from outer Solar System to terrestrial planets.

- This must occur before few Myr.

- Leaves planetary system in a configuration needed by *Nice* model.

- Note: The turnaround point is arbitrary.
Conclusions

Although there are some significant issues with our current understanding of planet formation, progress is being made.

1. Type I migration pushes planets into the Sun and icy bodies to 1 AU.
2. Mars is too small.
3. Core of giant planets take too long to form.
   - Planet-driven migration might solve these issues.
4. Type II migration produces hot Jupiters. Why did this not happen here?
   - Grand Tack- like evolution.

This talk can be found at www.boulder.swri.edu/~hal/talks.html.
We thank NASA’s Origins and OPR programs and the NSF for support.
1. Title
2. The $6 \frac{1}{2}$ Steps
3. Step IV: Late Stage
4. An Aside: Asteroid Belt Formation and the Origin of Earth’s Water
5. An Complication: Gas-Driven Planet Migration
6. Planetesimal-Driven Migration
7. Planetesimal-Driven Migration: The Case for Mars
8. But Wait — There is more
9. An EXTREME Case of Planetesimal-Driven Migration
10. Type II and the ‘Grand Tack’
11. Conclusions