The Formation of Planets from the Direct Accretion of Pebbles

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An Apple- and Microsoft-Free Presentation
A Pair Simulations

- Our Disk: \( \Sigma = \Sigma_0 r^{-1} \), \( h/r \propto r^{9/7} \), \( \alpha = 3 \times 10^{-4} \)
  - \( \Sigma_0 = 5 \times \text{MMSN} \).
  - Gas exponentially decays with half-life of 2 Myr.
  - Solar Solid-to-Gas Ratio.

- Split the simulation into 2 parts at the snow-line (2.7 AU).

- Convert some fraction \((f)\) solids to planetesimals:
  - Outer: \( f = 10\% \)
    - \( 100 < R < 1350 \) km (roughly Pluto size), \( n(R)dR \propto R^{-4.5} \).
  - Inner: \( f = 0.8\% \) \((50 \times \Sigma(AB))\),
    - \( 200 < R < 600 \) km (slightly > Ceres size), \( n(R)dR \propto R^{-3.5} \).

- Slowly create pebbles:
  - Spatially and temporally follows \( \Sigma \) out to 30 AU.
  - \( \tau_S \sim \frac{P_{\text{orb}}}{t_{\text{drag}}} = 0.1 - 0.6 \).
    - Have \( R \sim 4 - \sim 50 \) cm depending on \( a \).
  - Assume that pebbles can’t cross snow-line.

- Follow evolution with new dynamical/collisional code \textit{LIPAD}.
  - Modified to include just about everything.
Two Example Simulations

First calculations to reproduce the structure of the Solar System!

- Normal Earth and Venus, a small Mars, a low mass asteroid belt, and the gas giant planets.
Well Known Issues in Standard Planet Formation Models

1. The Meter Barrier:
   - Small objects stick due to electrostatic forces.
   - Large objects can be held together by gravity.
   - But it is not clear that $\sim 1\text{ m}$ will stick.

2. The Giant Planet Core Time-Scale Problem:
   - Cores of Jupiter and Saturn have to form before the gas goes away.
     - Disks last 3-5 Myr. (Earth took between 50 and 100 Myr to form!)
   - Standard model cannot build the core fast enough.

3. Mars is TOO small:
   - Standard model predicts that Mars should be larger than the Earth.
   - But, Mars is part of a gap in the distribution of material in the Solar System.
Example from Brauer, Dullemond, & Henning (2008)
The Basic Story

1. Dust particles begin to settle and grow in disk.

2. The presence of settling dust causes turbulence in the gas.

3. 10 cm — 10 m pebbles concentrate due to streaming instability or turbulence \(\Rightarrow\) gravitational instabilities.
   
   \((\text{Youdin} \ & \ \text{Goodman}; \ \text{Cuzzi} \ et \ al.)\)
   
   ▶ Predicts the first planetesimals are \(\sim 100 \rightarrow \sim 1000 \text{ km.}\)
   
   ▶ Only converts 10 – 50\% of pebbles to planetesimals.
   
   ▶ So, we have a bimodal distribution of objects.

4. Large planetesimals can accrete pebbles \textbf{verrrrrrry} effectively.
   
   \((\text{Ormel} \ & \ \text{Klahr}; \ \text{Lambrechts} \ & \ \text{Johansen})\)
   
   ▶ Because strong gas drag leads to pebbles becoming captured.
   
   ▶ Leads to HUGE cross section \( (> r_H)\).
   
   ▶ Only effective for large planetesimals.
Pebble Accretion

(Lambrechts & Johansen)
A single planetary embryo embedded in a disk of pebbles:

- Small objects cannot grow because encounters happen too fast for the gas to matter.
The Problem with Fast Pebble Creation

- The simplest assumption is that all the pebbles and planetesimals formed together. *(Lambrechts & Johansen)*

- Large planets grow in $\sim 1000$ years! ✓

- But, we end up with $\sim 100$ Earth-mass objects. *(Kretke & Levison)*
  - We get gas giants, but earths scatter through the system, destroying the Kuiper belt and terrestrial region.
  - This occurs because the capture cross section scales with $R_H$.
    - So, $R \sim R_H \Rightarrow \dot{M} \propto M^{2/3}$.
    - the largest objects become roughly the same size.
$t = 2100\, y$

$N > M$

$M > 1 M_\odot$: $N = 47$, $M = 79 M_\odot$
$t = 0 \text{ y}$

$\text{Mass (M}_\odot\text{)}$

$N = 0, M = 0 \text{M}_\odot$ for $M > 1 \text{M}_\odot$.
Slow Pebble Accretion

- If we let pebbles form slowly:
  - In original runs, planets grow before they interact.
    - System stays cold and then BOOM!
  - However in this case, the planets excite one another as the grow.
    - Smaller planets spend most of their time above the pebble disk. They can’t grow.
    - Larger planets can feed most of the time, so they can grow.
  - We end up with a few cores and a lot of small things.

So, this process can effectively make the giant planets.
Slow Pebble Accretion and Terrestrial Planets

Let’s look at what happens with slow pebble accretion: We find that the terrestrial planets form in 2 stages.

▶ **Pebbles Stage:**
  ▶ Little mass near 1.5 AU and almost none beyond 2 AU!
  ▶ Closer to the Sun ⇒ smaller objects can grow.
  ▶ For this disk, Ceres-sized objects can only grow to ∼1.5 AU.

▶ **Bamm-Bamm Stage:**
  1. Eat all planetesimals w/ \( a \lesssim 1 \) AU.
  2. Settle into a system of ∼20 small planets.
  3. Suffer an instability of 10s Myr ⇒ giant impacts.

▶ So, we have a single physical process that can make:
  1) Earth and Venus.
  2) Low-mass Mars,
  3) Low-mass asteroid belt.
A single planetary embryo embedded in a disk of pebbles:
To zeroth order $R_c \propto R_H e^{-\xi}$, where $\xi$ is $\text{func}(R, M_p, \Sigma, h)$. So:
Conclusions

▶ There are some issues with the classical model of planet formation.
   1. Cannot grow beyond $\sim 1\,\text{m}$.  
   2. Cores of giant planets take too long to form.  
   3. Mars is too small and the asteroid belt is nearly empty.
▶ We argue that slow pebble accretion might solve these problems.
▶ In particular, we present a new scenario:
   ▶ A small number of planetesimals initially form.
   ▶ Pebbles grow on a timescale of 100,000 y — 1 Myr.
▶ This one scenario can reproduce most of the structure of the planetary system!

This talk can be found at www.boulder.swri.edu/~hal/talks.html. We thank NASA’s SSERVI program and the NSF for support.
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