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:** $\Sigma = \Sigma_0 r^{-1}, \ h/r \propto r^{9/7}, \ \alpha = 3 \times 10^{-4}$
  - $\Sigma_0 = 5 \times$ 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 $>\text{Ceres size}$), $n(R)dR \propto R^{-3.5}$.

- **Slowly create pebbles:**
  - Spatially and temporally follows $\Sigma$ out to 30 AU.
  - $\tau_S \sim P_{orb}/t_{drag} = 0.1 - 0.6$.
    - 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 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.
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. 
   
   (Youdin & Goodman; Cuzzi et al.)
   
   - Predicts the first planetesimals are $\sim 100$ — $\sim 1000$ km.
   - Only converts 10 – 50% of pebbles to planetesimals.
   - So, we have a bimodal distribution of objects.

4. Large planetesimals can accrete pebbles *verrrrrrrry* effectively. 
   
   (Ormel & Klahr; Lambrechts & Johansen)
   
   - Because strong gas drag leads to pebbles becoming captured.
   - Leads to HUGE cross section ($> r_H$).
   - Only effective for large planetesimals.
$t = 0 \, y$
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.
$t = 2100 \text{ y}$

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

$t = 0 \text{y}$
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.
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1. Title
2. Two Example Simulations
3. Two Example Simulations
4. The Basic Story
5. The Problem with Fast Pebble Creation
6. Slow Pebble Accretion
7. Slow Pebble Accretion and Terrestrial Planets
8. But wait, There’s more
9. Mercury
10. Conclusions