What is Planet Formation?
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Solar System

Protoplanetary Disks

Exoplanets
What is Planet Formation?

Solar System

Protoplanetary Disks

Exoplanets

• Giant Planets / Hot Jupiters

• Super-Earths/Mini-Neptunes

• Earthlike (?) Planets
"Small" planets are more common than giant planets

Fressin et al. 2013
Today’s Lecture

1. Exoplanet Populations from Kepler
2. Planet Formation in the Solar System
3. Exoplanet Formation
4. Planet Migration

Phil Armitage updated lecture notes:
1. Exoplanet Populations
Known Exoplanets with Mass Measurement

- Hot Jupiters
- Long-Period Giants
- "Super-Earths/Mini-Neptunes"
- Radial Velocity Transits
Exoplanets with Kepler

Batalha et al. 2012

blue (first discovered)
yellow (last discovered)
Why are these different?
Survey Bias:
Giant planets are preferentially found around stars that are rich in metals and more massive (support the formation of the core of giant planets first followed by accretion of nebular gas).

\[ [\text{Fe/H}] = \log(n_{\text{Fe}}/n_{\text{H}}) \]
Radial Velocity Sensitivity Bias:
Giant planets are easier to detect

Jupiter RV amplitude: 12 m/s (5 au)
Super-Earth at 0.1 au: \(~1\) m/s
How is Kepler different?

- 0.95m telescope
- Main mission: 2009–2013
- Mission goal: estimate frequency of habitable zone earth-sized planets around sunlike stars

http://kepler.nasa.gov
Kepler monitored over 100,000 stars for four years
Kepler-62f, an Earth-size planet in the HZ

Kepler is good at finding small planets!

Precision: 0.01 % (~10 ppm)
>100,000 stars
1200 planets
4696 “planetary candidates”

Transit probability (Rstar/a):
Hot jupiter: ~30%
Earth: 0.5 %

"For each planet Kepler detects, there are on average 10-100 undetected planets"

Stars with planets: > 40-100%
“typical” Exoplanet system

2-3 EarthRadii, \( P \sim 10 \) days

Terrestrial Planets

Batalha et al. 2012
“typical” Exoplanet system

Weiss & Marcy 2015

2-3 Earth Radii,
~5-10 Earth Masses
2. Planet Formation in the Solar System
Our Solar System

Two main features:

1. Planets have nearly circular orbits going in the same direction in nearly the same plane

2. There are two types of planets: rocky (inner) and gas giants (outer)
**Contraction:** As it contracts, the cloud heats, flattens, and spins faster, becoming a spinning disk of dust and gas.

**Condensation:** Hydrogen and helium remain gaseous, but other materials can condense into solid “seeds” for building planets.

- A large, diffuse interstellar gas cloud (solar nebula) contracts due to gravity.
- The Sun will be born in the center.
- Planets will form in the disk.
- Warm temperatures allow only metal/rock “seeds” to condense in the inner solar system.
- Cold temperatures allow “seeds” to contain abundant ice in the outer solar system.
- Terrestrial planets are built from metal and rock.
Planet formation takes place over a range in size ($10^{13}$) and mass ($10^{40}$)

Today focus on planetesimals $->$ planets / cores
Minimum Mass Solar Nebula

Distribute planet mass over annulus stretching to next planet

\[ \Sigma = 1.7 \times 10^3 \left( \frac{r}{\text{AU}} \right)^{-3/2} \text{ g cm}^{-2} \]

Hayashi 1981

Weidenschilling 1977
Isolation Mass

Mars-Sized Planetary Embryos

Giant Planet Cores

How massive can a protoplanet grow from a planetesimal disk?

$$M_{iso} = \frac{8}{\sqrt{3}} \pi^{3/2} C^{3/2} M_*^{-1/2} \Sigma_p^{3/2} a^3.$$  

**Fig. 1.** The mass distribution of embryos predicted by (10), for parameters such that the embryo at 1 AU has a 0.1 \( M_\oplus \). The snowline is set here at 3.5 AU.

Morbidelli et al. 2015
How to grow Earth from Mars-sized objects?

Raymond et al. 2009
How to grow Earth? (no Jupiter)

Ciesla et al. 2015
Jupiter Formation: Core Accretion

1. Core Formation (Isolation Mass)

2. Envelope accretion, cooling-limited (contraction, planetesimal accretion) M<10 Mearth

3. Runaway gas accretion (M_{envelope}>M_{core}, critical core mass) M>10 Mearth

Pollack et al. 1996
Planet Formation in the Solar System

1. Terrestrial Planets form from Mars-sized cores

2. Giant planets cores (10 Mearth) grow directly from planetesimals followed by runaway gas accretion
3. Exoplanet Formation
What increase in surface density needed to form typical exoplanet system “in situ”?  

Terrestrial Planets  
2-3 Earth Radii, P~10 days

Batalha et al. 2012
Minimum Mass Extrasolar Nebula

Disk mass ~5-10 times MMSN
In Situ Formation:

Hansen & Murray 2012

50 Mearth inside 1 au
protoplanetary disks ~10-100 Mearth at ~10-100 au
4. Planet Migration
Planet Migration in Protoplanetary Disk

Planet Perturbs the disk
(~Earth Mass)
Planet Migration in Protoplanetary Disk

Torque Equilibrates Velocities
Planet Migration in Protoplanetary Disk
Planet Migration in Protoplanetary Disk

Exterior torque:
Gas pushed outwards, planet pushed inwards

Interior torque:
Gas pushed inwards, planet pushed outwards

Inward or outward depending on sum of torques!
were trapped in resonance with the migrating core and ended up interior to its orbit. Two small embryos migrated inward in order to dominate its vicinity and migrate outward. This demonstrates the importance of core mass: a core must be more massive than its neighbors to migrate inward. The presence of other, nearby embryos prevented it from migrating inward. Therefore, the fraction of systems with potential giants may be even faster than predicted in our model. Of course, the fraction of systems with potential giants is a crude tool but it helps gauge the potential for giant formation.

We performed a simple experiment to test the efficiency of core formation. We ran simulations with the same gas disk model between the stellar metallicity and the frequency of hot super-Earth objects. From the simulations, we found that 12% of the systems (12/100) have embryos that cross the migration-reversal threshold. We also found that 42% of the systems (42/100) become actual giant planet core candidates. Nonetheless, these objects have all of the conditions needed to form full-fledged gas giants.

In this model, giant planet cores are represented by embryos that are more massive than their neighbors. The embryos migrate outward and are generated in a region where Type-I migration takes place. Type-I migration is controlled by the disk evolution, which determines the zero-torque radius. In addition, giant impacts between embryos may actually increase the mass of the embryos, which can lead to the formation of giant planets.

Our simulations suggest that giant planet cores formed in just 5% (5/100) of the simulations. This is consistent with the observations that only 5 objects have all of the conditions needed to form full-fledged gas giants.
Type-II Migration: Mostly inwards

The orbiting planet’s gravity nudges particles in the disk... causing material to bunch up. These dense regions in turn tug on the planet, causing it to migrate inward.

a giant planet opens a gap
Planet Migration in Protoplanetary Disk
Exoplanet Formation

- Solar System:
  Inner disk: Mars-sized cores + assembly
  Outer Disk: Jupiter core + gas accretion

- Kepler Exoplanets:
  In Situ formation in massive disk or type-I migration

- Giant Exoplanets:
  Core accretion as Solar system (+Type-II migration)