Planetary Geology: Era of Planetary Formation
Main Concepts

• Quick Review: Planetary Accretion
• Resonance & Migration
• “Grand Tack” model
• “Nice” model
• Remaining Issues?
The rotating disk surrounding a protostar consists of:

- gases (primarily H and He)
- heavier elements (Si, Fe, C, Ni, etc.)
- ices (water, methane, ammonia; covers dust particles)

Some regions become more concentrated as materials collide and stick together. This forms **planetesimals**.

Planetesimals eventually become large enough to exert gravitational pull on each other. They begin to collide and grow rapidly in size. They can then become **protoplanets**.

This process is often referred to as **planetary accretion**.
$10^5 - 10^6$ yrs
$10^6 - 10^7$ yrs
$10^6 - 10^8$ yrs
COMPOSITION VARIES WITH DISTANCE

proto-Sun

metal, rock, gas

snow line

metal, rock, ice, gas

spike in availability of solids

NOT TO SCALE!
The planets in our Solar System exhibit a dramatic change from rocky planets with thin or absent atmospheres (terrestrial planets) to large planets dominated by gas and liquid (gas giants).

This is clear when comparing the average density of the planets.

The terrestrial planets have a higher bulk density because of metallic cores (Fe, Ni, S) overlain by silicate mantle and crust.

In contrast, the gas giants have rather small silicate/iron cores that are overlain by much lighter elements (liquid and gaseous H).
As planets undergo accretion, the heavy elements (Fe, Ni, S) will tend to sink to the center to form a metallic core. This is called **planetary differentiation**, and there are still many unanswered questions about the specifics of how this process occurred.

The lighter elements (Mg, Ca, Al, etc.) will remain outside the center to form the mantle. The outermost layer of the mantle is exposed to the atmosphere/space and will cool rapidly to form the initial crust.
EARLY PLANET FORMATION

Disk of gas and dust

Dust settles, grows to pebbles

Pebbles grow into 100 – 1000 km diameter planetesimals

NOT TO SCALE!
Swarms of planetesimals 100 – 1000 km diameter in size

Make Moon- to Mars-sized embryos; giant planets form

Embryos and giant planets in $10^5$ to $10^6$ years!
EARLY PLANET FORMATION

Gas goes away

Embryos collide to make terrestrial planets

Finish terrestrial planets in 30 – 100 million years

NOT TO SCALE!
Next: Collisions & Migration

What is the evidence for migration of planets?

EARLY PLANET FORMATION

NOT TO SCALE!
Disk density decreases
Orbital periods increase
Formation time increases

snow line

spike in availability of solids

Kwamikagami
Problems & Questions:

It takes $\sim 10^9 - 10^{10}$ years to make Neptune at its current location....

...but gas in the disk lasts a few $10^6$ years.

How do we get water & other volatiles to the inner planets?

$\sim 700$ Myr after start of solar system there was an increase in impact events in inner solar system..... what caused this late heavy bombardment?
ORBITS

Two body problem is stable (Kepler’s Laws)

eccentricity
inclination
3+ OBJECTS

Orbits become chaotic

Close encounters change orbit of small thing

Throwing out *enough* little things can shift orbit of big bodies
RESONANCES

Can destabilize orbit and send objects to new places in (or out of) the Solar System

Two kinds:

- Mean motion
- Secular (orbital wiggle)
THE GRAND TACK MODEL

Possible explanation for small size of Mars

Migration of giant planets while gas is present (first 5 million years of solar system history)

Walsh et al. (2011)
GRAND TACK: START

Walsh et al. (2011)
THE GRAND TACK MODEL

Dry planetesimals

Wet planetesimals

Planets:
  Jupiter
  Saturn
  Uranus
  Neptune

Walsh et al. (2011)
GRAND TACK: INWARD MIGRATION

Walsh et al. (2011)
GRAND TACK: REVERSAL

eccentricity

asteroid belt

J    S

distance from Sun

Walsh et al. (2011)
THE GRAND TACK : SUMMARY

Happens while gas is still in the disk!

Jupiter scatters dry planetesimals on way in

Saturn and Jupiter reach resonance

Both migrate out, scattering wet and dry

 Sends wet and dry to inner Solar System

Walsh et al. (2011)
RECAP

Availability of solids affects accretion time

Models of the protoplanetary disk and exoplanets suggest planets violently migrate

Gravitational interactions among many bodies allows orbits to change

Grand Tack model explain aspects of our Solar System—but remains a model!
Motivated by nature of small body reservoirs and timing of Late Heavy Bombardment
Set much later than Grand Tack
Planetesimal-driven migration

Tsiganis et al. (2005); Gomes et al. (2005); Levison et al. (2005)
THE NICE MODEL: SETUP

today

start of Nice

icy planetesimals

Tsiganis et al. (2005); Gomes et al. (2005); Levison et al. (2005)
Jupiter
Saturn
Uranus
Neptune
icy planetesimals

Tsiganis et al. (2005); Gomes et al. (2005); Levison et al. (2005)
Tsiganis et al. (2005); Gomes et al. (2005); Levison et al. (2005)
THE NICE MODEL: ~800 MYR

~800 myr Jupiter & Saturn cross a resonance
Destabilizes disk, flings planetesimals around and out of the Solar System

Tsiganis et al. (2005); Gomes et al. (2005); Levison et al. (2005)
THE NICE MODEL: CONSEQUENCES

Inner planets bombarded by planetesimals (late heavy bombardment)

Populate:
- Kuiper belt
- Oort cloud
- Jupiter Trojans
- main asteroid belt

Tsiganis et al. (2005); Gomes et al. (2005); Levison et al. (2005)
THE NICE MODEL: SUMMARY

Giant planets formed closer together & closer to Sun

Migrate outward because of interactions with disk of icy planetesimals

Cross orbital resonance, disk destabilizes

Planetesimals scattered into, around, and out of Solar System

May explain Trojan asteroids @ Jupiter

Tsiganis et al. (2005); Gomes et al. (2005); Levison et al. (2005)
Ad hoc choice of initial planet orbits.

What about interactions w/ inner planets and planetesimals?

Nice 2.0 model deals with some of these issues, including more generic initial orbit of giant planets.

But....other researchers/models have shown that current structure of solar system is perhaps best reproduced by starting w/ 5 giant planets!
RECENT STUDY SUGGESTS:

most models where giant planets migrate inward result in ejection of Mars, Mercury

Any inward migration of giant planets must have been very early, before terrestrial planets formed

Therefore this migration can’t explain Late Heavy Bombardment at ~3.8 Ga.

Possible that other (5th, 6th?) icy giant planets and many inner terrestrial ‘planets’ were ejected from early Solar System.