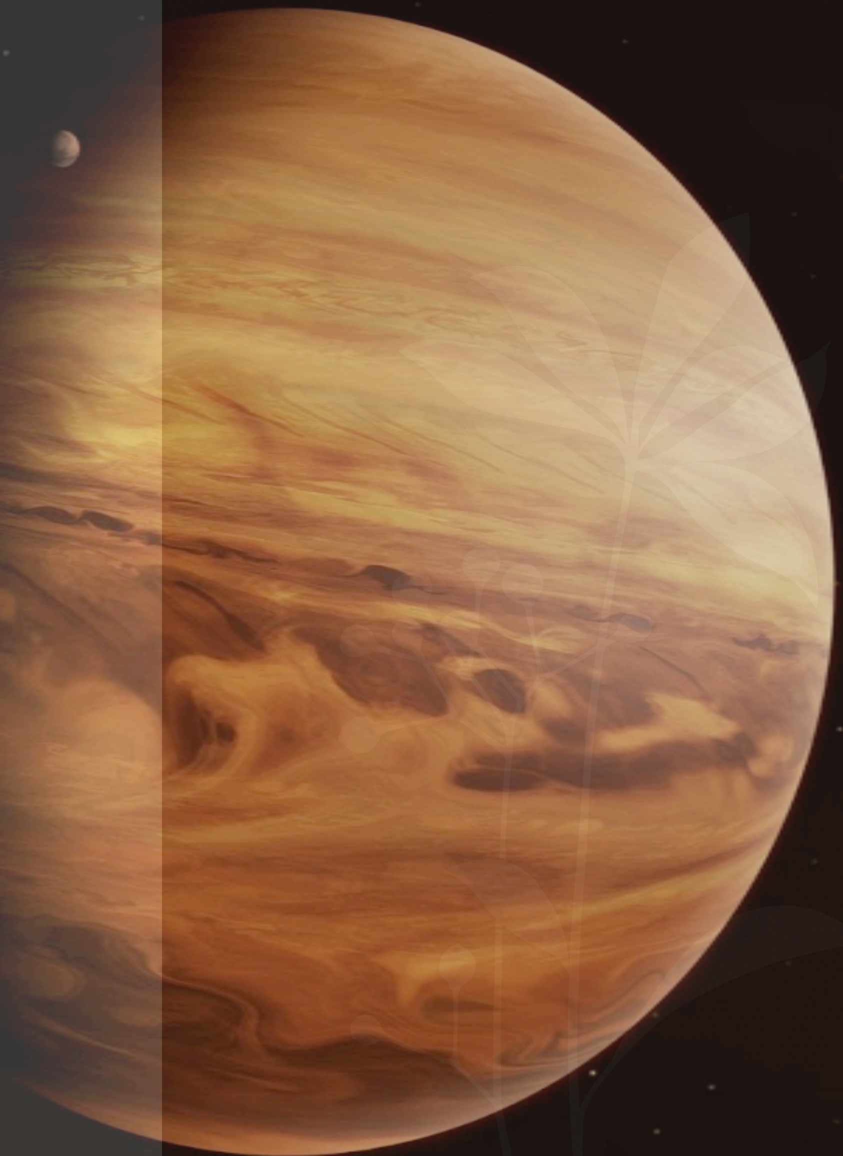

Giant Planet Formation, Evolution and Internal Structure

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PPVI, Heidelberg, Germany

Paper Outline

Introduction

Giant Planet Formation Models

- Core Accretion
- Disk Instability

Post-Formation Evolution

Giant Planet Interiors

- Solar System
- Exoplanets

The Future

The Importance of Giant Planets

- **Shape the architecture of planetary systems**
  - Large mass
  - Fast formation
    - Excitation of small bodies, volatiles delivery

- **Composition**
  - Provide information on the physical and chemical properties of proto-planetary disks

- Until ~1995: Giant planet formation models try to fit the observed properties of the planets in the solar system.

- From ~2000: masses and radii of extra-solar giant planets. Modifications of formation and evolution models.

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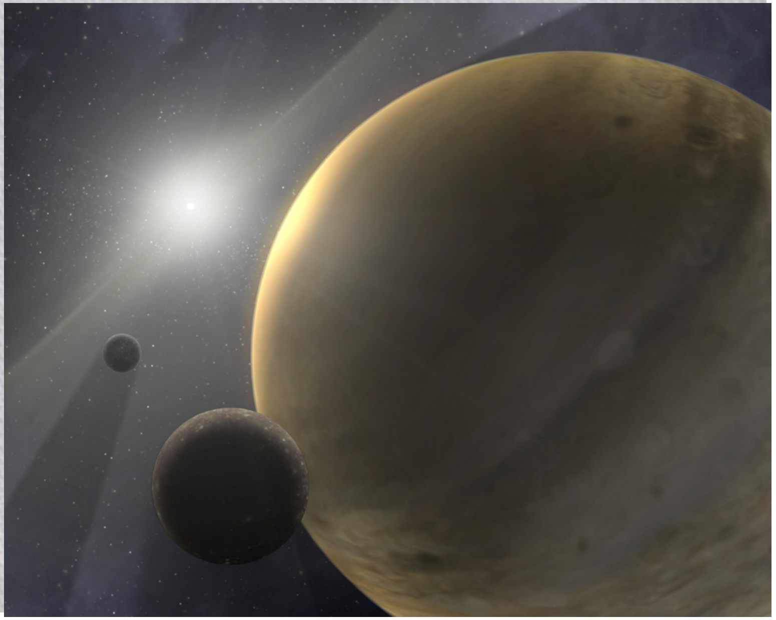

We are entering an era of planetary characterization: Can composition and internal structure reveal information on formation mechanism?

In the Solar System

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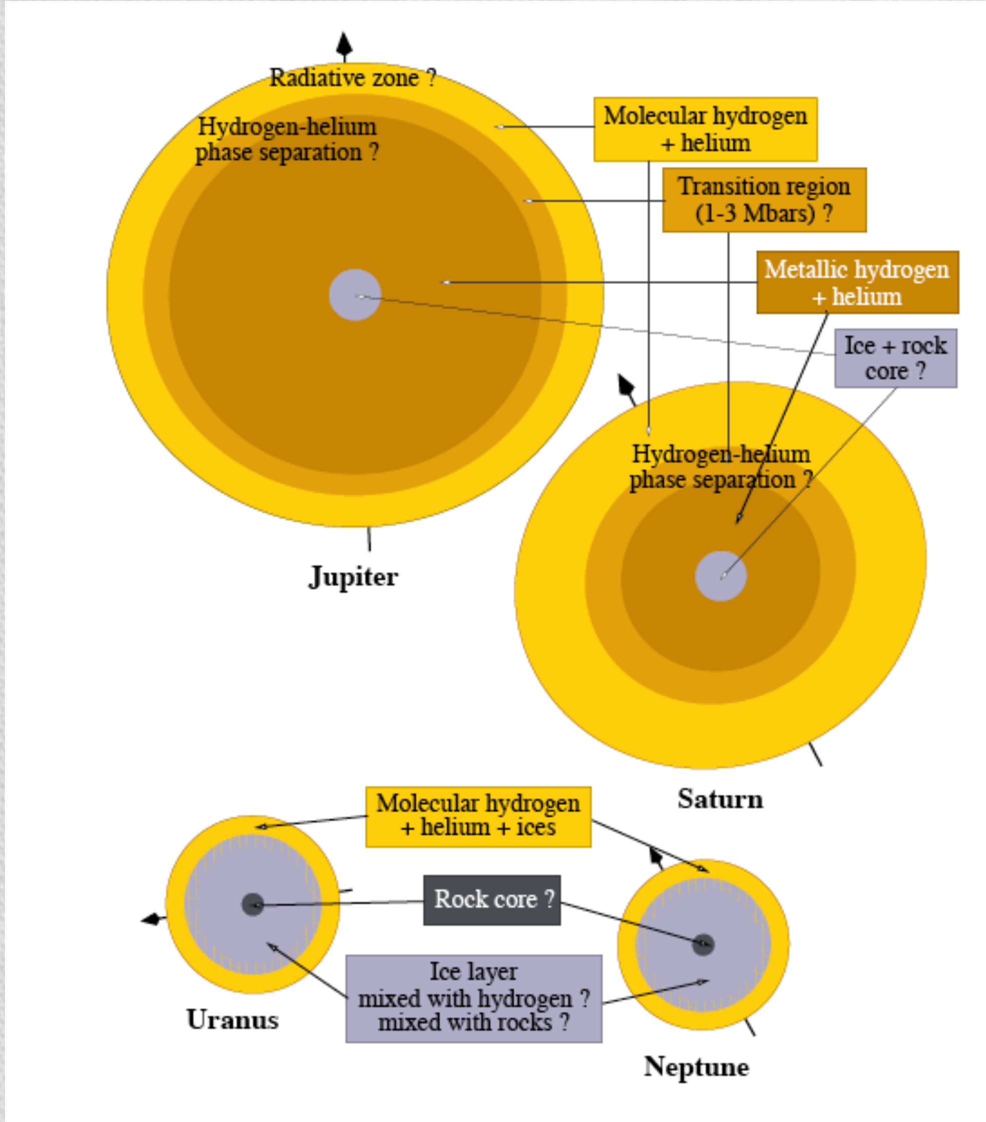
Jupiter, Saturn, Uranus, Neptune

- Giant planets exist at large radial distances (> 5 AU)

- Mass is decreasing with radial distance.

- Metal enrichment is increasing with decreasing mass.



Wuchterl et al., 2000. PPIV. Uni. Arizona Press.

Exoplanet Outlook:

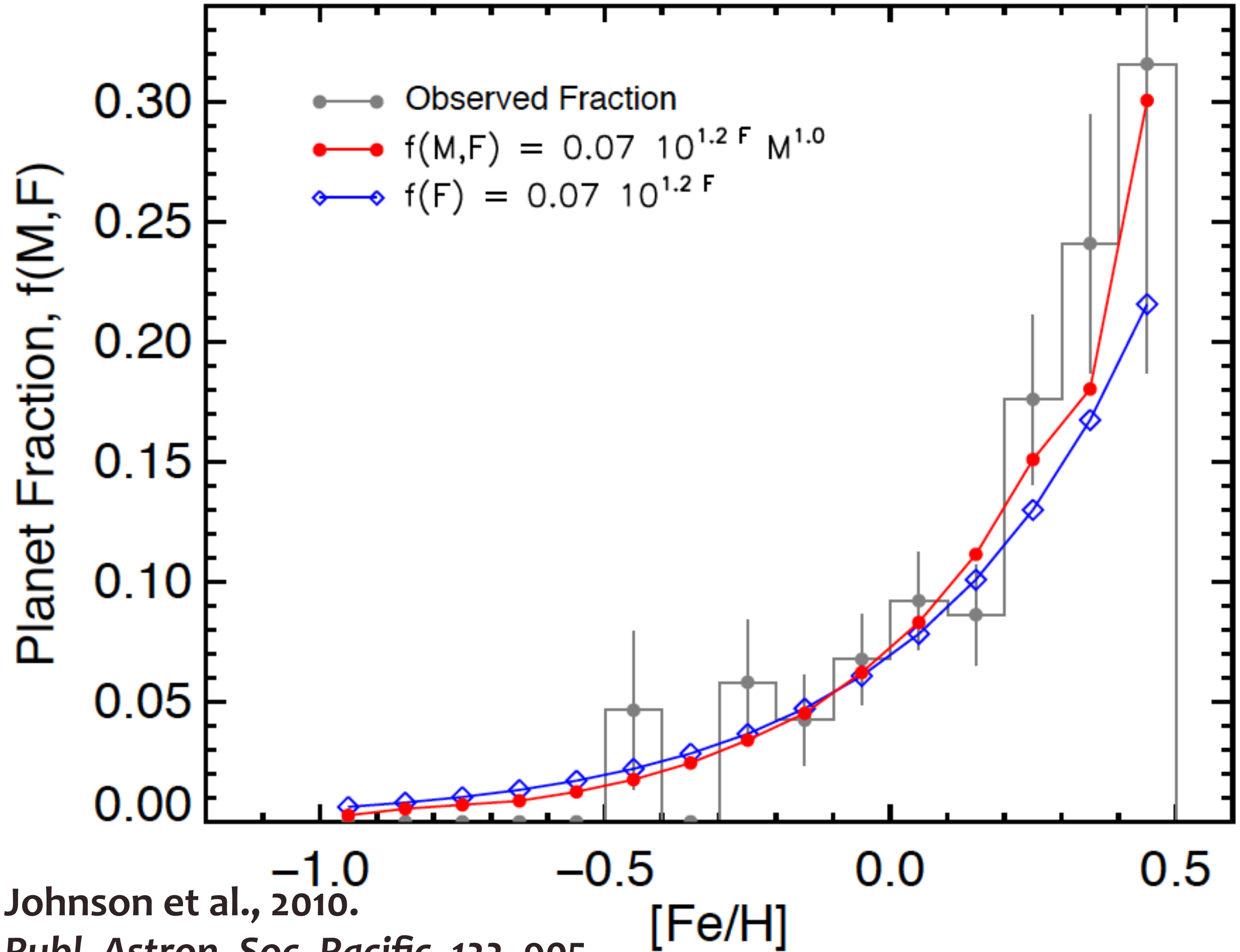
- Many observed extra-solar giant planets but they seem to be less common than small planets.
- Overall giant planet occurrence rate ~ 5-20% (depends on stellar mass and metallicity [Fe/H]).
- Giant planets exist at VERY small radial distances.
- Giant planets also exist at very large radial distances (direct imaging).

Exoplanet Outlook:

- Disk observations: disk lifetime < 10 Myrs; typical disk mass 0.01 - 0.1 $M_{\odot}$.
- Transiting giant planets consist of ~10-100 $M_{\oplus}$ of heavy elements.
- Giant planets have been observed around M-dwarf stars and metal-poor stars.

Planet-Metallicity Planet-Occurrence Correlation

Main sequence stars



Johnson et al., 2010.
***Publ. Astron. Soc. Pacific*, 122, 905.**

see also:
Santos et al., 2004.

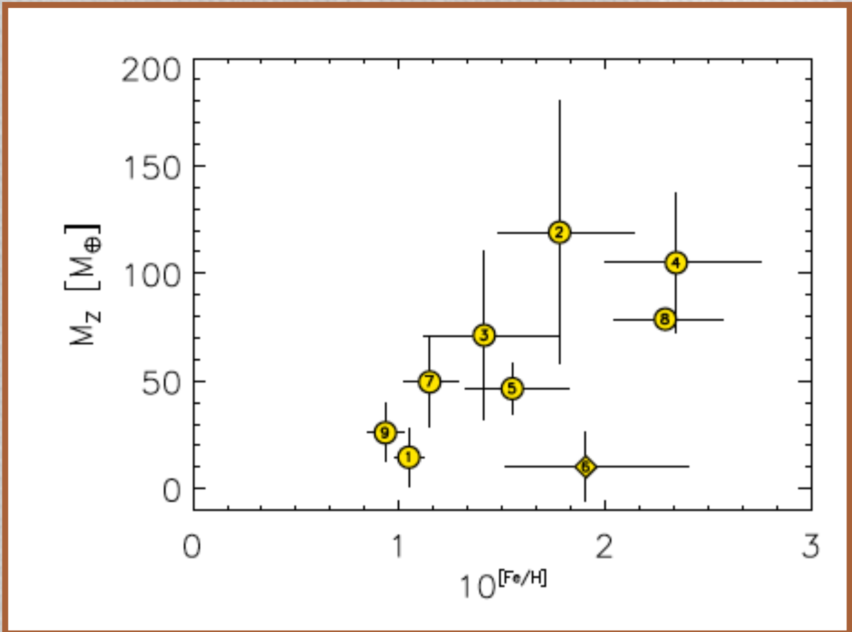
Fischer & Valenti, 2005.

Planet-Metallicity Stellar-Metallicity Correlation

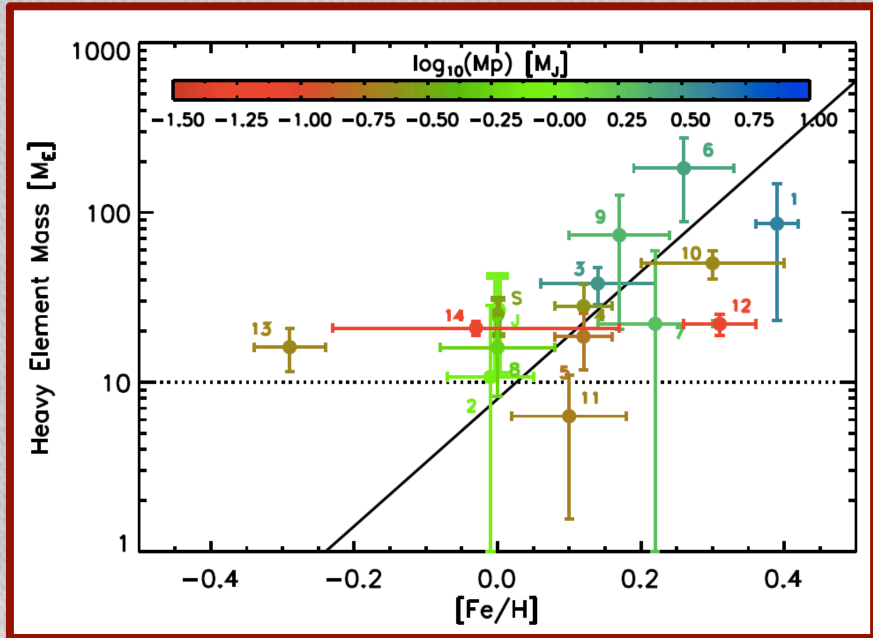
Giant planets around metal-rich stars have more heavy elements

More solids in the disk – more heavy elements in the planets

see also Burrows et al., 2007.



Guillot et al., 2006. A&A, 453, L2.



Miller and Fortney, 2011. ApJ, 736, L29.

Planet-Metallicity Stellar-Metallicity Correlation

A word of caution

Determination of stellar metallicity is complex

Data are still limited to strongly irradiated planets

This correlation is found using ***models*** and is not directly observed

In fact, the **planetary mass** is a better predictor of **metal enrichment** than stellar metallicity, as lower-mass planets tend to be more enriched over their parent star metallicity (**Miller & Fortney, 2011**).

Two Giant Planet Formation Models

Core Accretion:

- Planetesimal coagulation and core formation followed by accretion of a gaseous envelope.

Disk Instability:

- Formation as a result of gravitational fragmentation in the proto-planetary disk.

See review papers:
Lissauer & Stevenson, 2007. PPV.
Durisen et al., 2007. PPV.

Core Accretion

A giant planet is formed through the following three steps:

1. Accretion of dust particles and planetesimals results in a core of a few $M_{\oplus}$, accompanied by a low-mass gaseous envelope.
2. Further accretion of gas and solids: the envelope grows faster than the core until the crossover mass is reached.
3. Runaway gas accretion with relatively small accretion of solids.

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See review by:
D'Angelo et al. 2011. Exoplanets, S. Seager, Arizona Press.

- Starting with an embryo (~0.01-0.1 $M_\oplus$) and planetesimals (chapter by Johansen et al.)

Core accretion rate:

Accretion rate of surrounding planetesimals (Safronov, 1969):

$$\frac{dM_{solid}}{dt} = \dot{M}_{core} = \pi R^2_{capt} \Omega \sigma_s F_g$$

where $\pi R^2{}_{capt}$ is the geometrical cross section, Ω is the orbital frequency, σ_s is the solid-surface density, F_g gravitational enhancement factor.

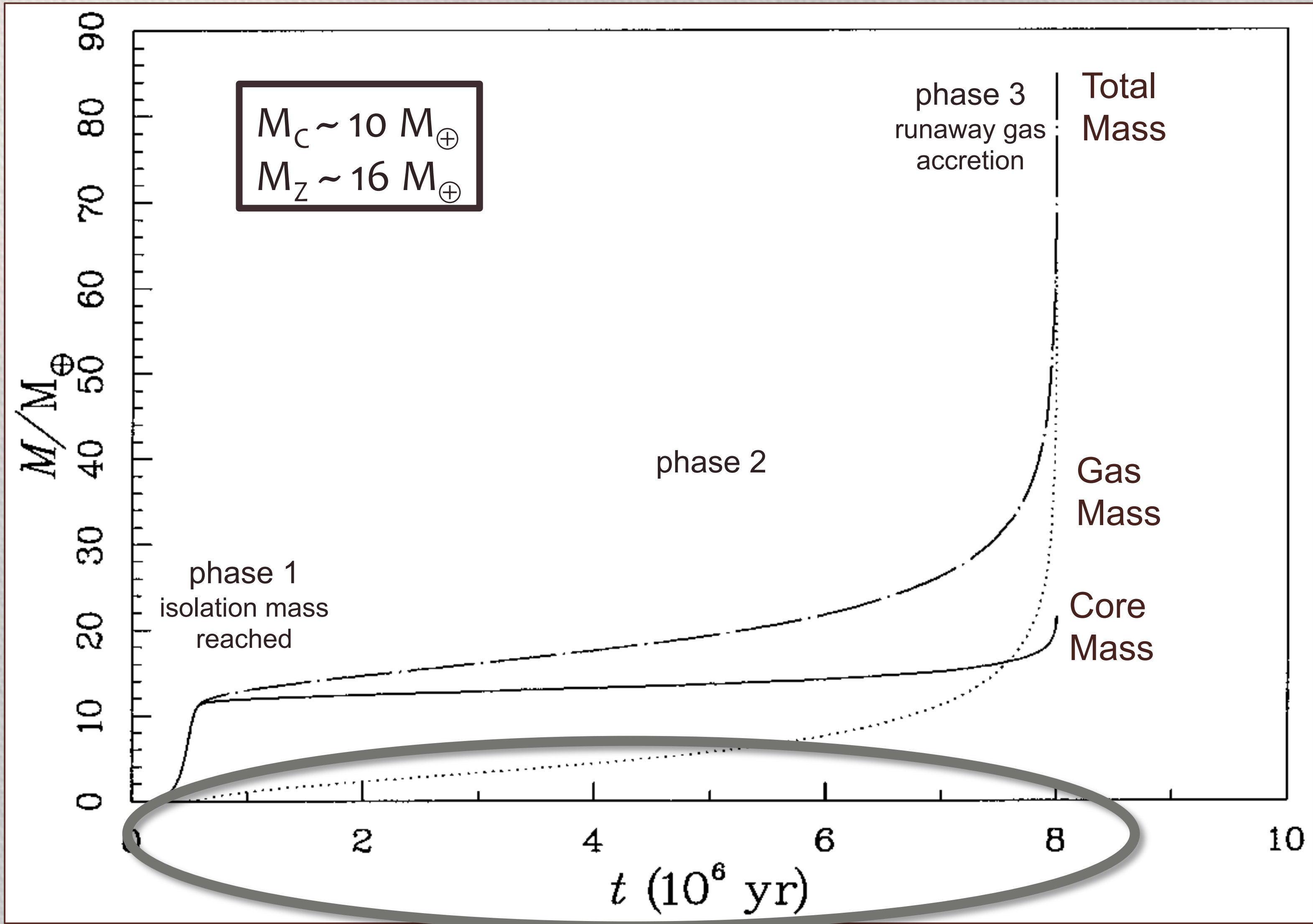
Envelope accretion rate:

- As the envelope contracts more gas is added to the growing planet

Runaway gas accretion:

- As $M_{core} = M_{env}$ → fast contraction & high gas accretion rate

A standard core accretion model for Jupiter's formation



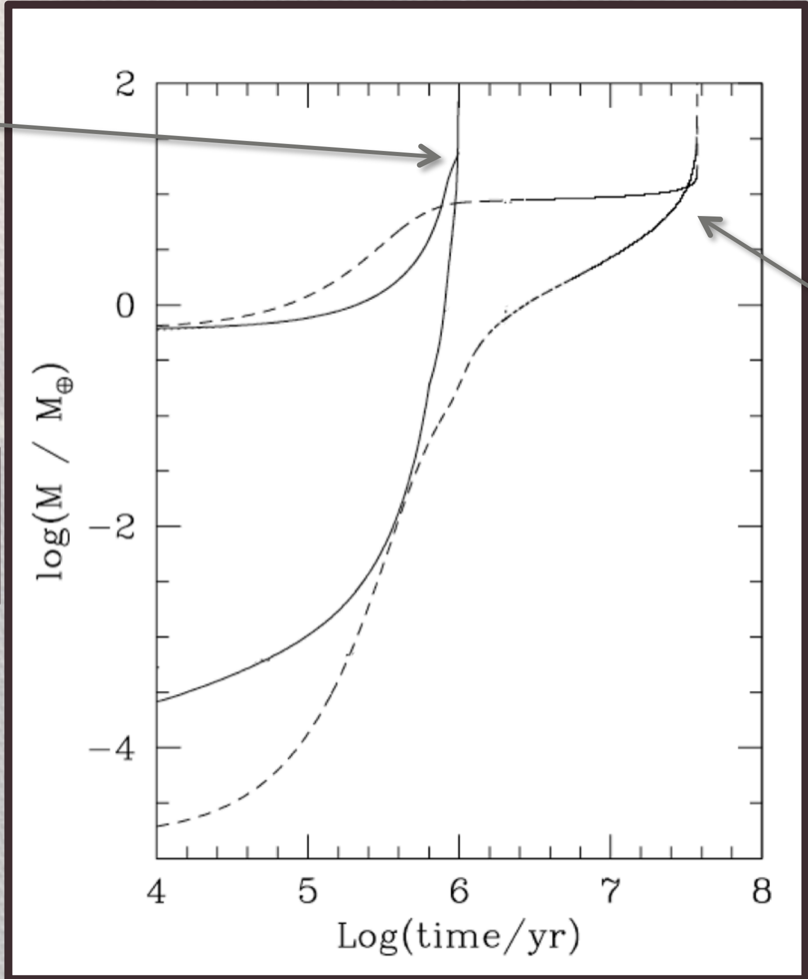
Pollack et al., 1996. Icarus, 124, 62.

$d = 5.2\,\mathrm{AU}$ $\sigma_{solids} = 10\,\mathrm{g\,cm^{-2}}$

$T_{neb} = 150\,\mathrm{K}$ $\rho_{neb} = 5 \times 10^{-11}\,\mathrm{gcm^{-3}}$

Reducing formation timescale by migration:

a migrating planet starting at 8 AU (no gap)

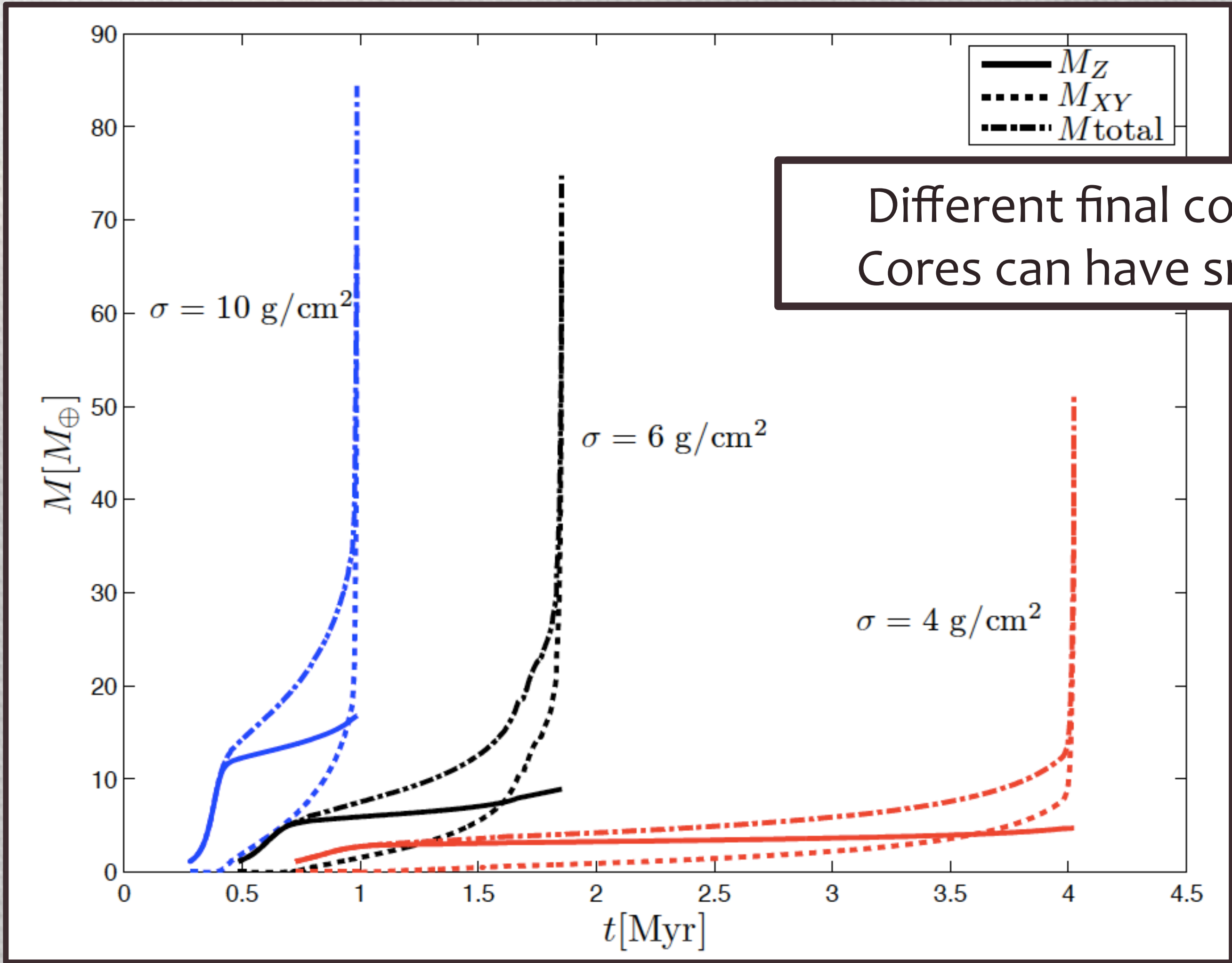


in situ formation 5 AU

A migrating Jupiter has $M_Z \sim 30\ M_{\oplus}$

Total mass of heavy elements (core+envelope) and mass of the envelope (H/He) vs. time, until the cross- over mass is reached.
Adapted from ***Alibert et al., 2005.***

Reducing formation timescale by opacity reduction due to grain settling and coagulation:



Different final compositions;
Cores can have small masses!

Movshovitz et al. 2010. Icarus, 209, 616.

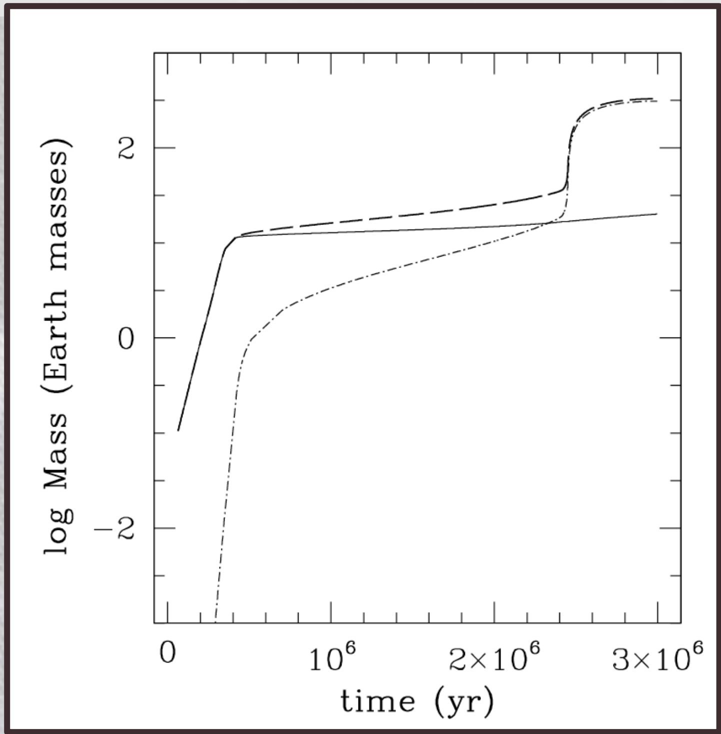
Updated Models:

•Accretion is terminated by a physical mechanism (disk dissipation/gap opening)

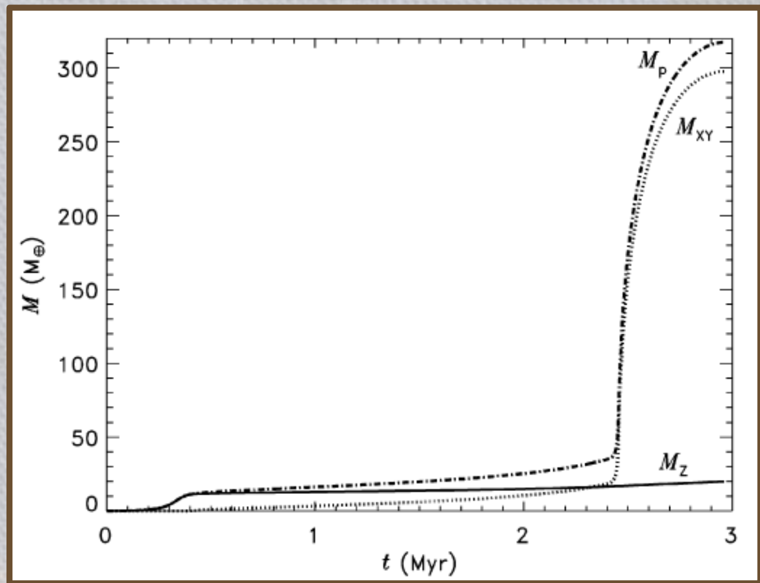
➔ final mass is better determined (depends on disk viscosity, surface density, etc.)

•**Alibert et al. 2005, Alibert et al. 2011:**

include migration, disk interactions, and other planets.



Lissauer et al. 2009. Icarus, 199, 338.



Lissauer et al. 2009. Icarus, 199, 338.

Core Accretion: predicted composition

Giant Planets formed by *CA* can have a range of metallicities:

$Z_{planet} < Z_{\star}$: accreted gas is metal-poor & core mass is small

$Z_{planet} \sim Z_{\star}$: accreted gas has stellar composition & core mass is small or accreted gas is metal-poor & core mass is large

$Z_{planet} > Z_{\star}$: accreted gas has stellar composition & core mass is large and/or much planetesimals are accreted during rapid gas accretion

… and of course other options are possible…

Core Accretion: predicted core mass

Giant planets have cores, but their masses ranges from several to tens of $M_\oplus$.

Models typically assume that the accreted planetesimals reach the core but in fact once $M_{core} \sim 2\ M_\oplus$ the planetesimals dissolve in the envelope.

Even if the primordial cores are massive the cores can get eroded with time.

Core Accretion: dependence on parameters

Effect of position in the disk

Without significant migration: optimum location of formation 5-10 AU for 1 $M_\odot$

Stellar mass

Assuming disk mass is scaled with stellar mass, formation is favorable for larger stellar mass until ~1.5 $M_\odot$. For $M_\star > 1.5\ M_\odot$ disk lifetime is thought to decrease.

Stellar metallicity

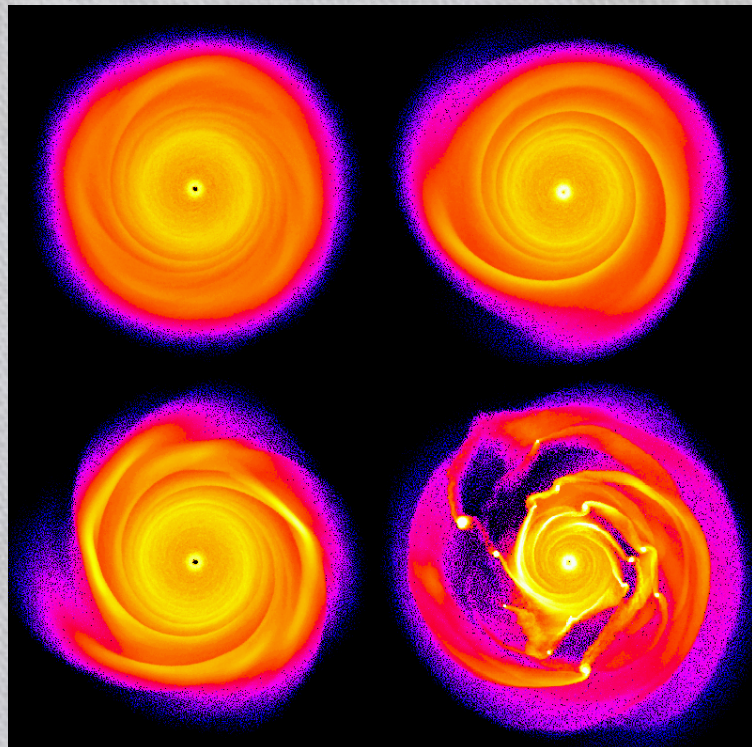
Disk metallicity increases with stellar metallicity – core formation is more efficient: giant planets can be formed.

Disk Instability

Giant planet formation via disk fragmentation

Formation timescale ~ 1000 years

Occurs at large radii



Mayer et al. 2002. Science, 298, 5599

Review papers:

Durisen et al., 2007. PPV, 607.

D'Angelo et al., 2011. Exoplanets, S. Seager, Arizona Press.

Disk Instability

- Toomre criteria (Toomre, 1964. ApJ, 139, 121):

$$Q = \frac{c_s \Omega}{\pi G \sigma_g}$$

Ω = angular velocity
c_s = sound speed
G = gravitational constant
σ_g = surface density

For an infinitesimally thin disk:

$Q > 1$ = stable

$Q < 1$ = unstable

Masses of clumps? Still debated 1-10 M_J

Disk Instability

- Fragmentation is conditioned by the ability to cool

Disks will fragment when

$\beta_{crit}<3$ for $\beta=t_{cool}\Omega$ (specific heat ratio γ=2)

(see e.g., Gammie, 2001; Rice et al. 2004)

β_{crit} could in fact be larger and depends on: Equation of state (**Rice et al. 2005**), disk's thermal history (**Clarke et al., 2007**), star and disk properties (**Meru & Bate, 2011**), etc.

Disk Instability

- Clump Evolution of planets with a few M_J

(**DeCampli & Cameron ,1979**):

Pre-collapse evolution: 10^3-10^6 yrs, clumps are extended (R~AU) and cold (H_2)

Dynamical collapse: dissociation of H_2

Long-term evolution: clumps are compact and dense, R~ a few R_J, 10^9 yrs

→ similar to core accretion

Determination of pre-collapse timescale:

1D: planetary mass, distance from star, composition (metallicity/opacity)

3D: angular momentum, non-spherical shape

The role of Metallicity/Opacity

Efficiency of DI

Fragmentation depends on disk thermodynamics, which is affected by the disk opacity and mean molecular weight. Both of these scale directly with the disk metallicity.

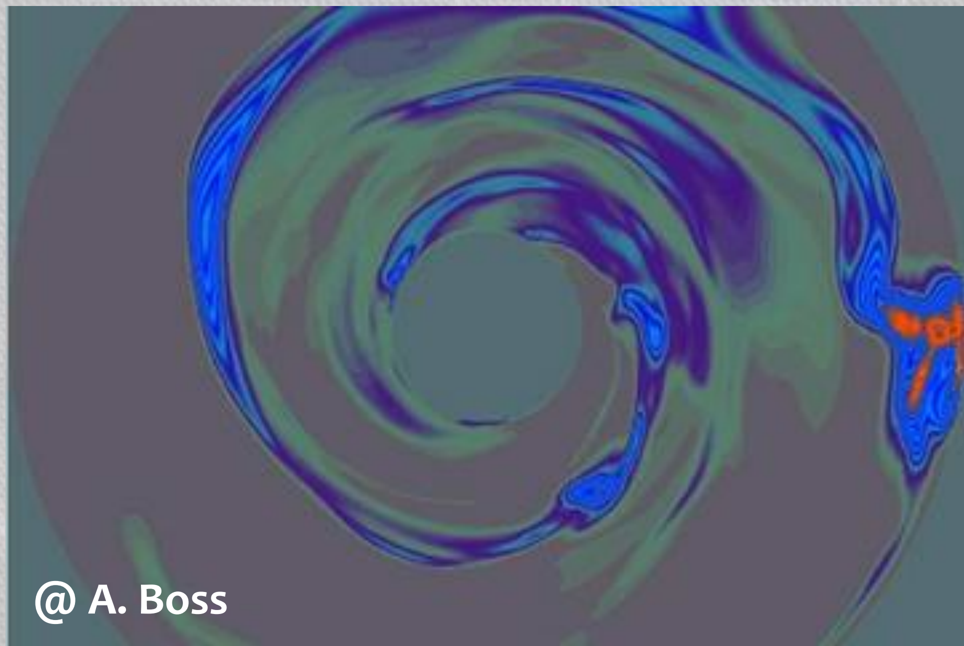
Cai et al. 2006; Meru & Bate, 2010:
more efficient fragmentation with reduced opacity

Boss, 2002; Mayer et al., 2007:
fragmentation is insensitive to opacity

Still work in progress…

Composition

The composition of disk instability giant planets can range from sub- to super- stellar!

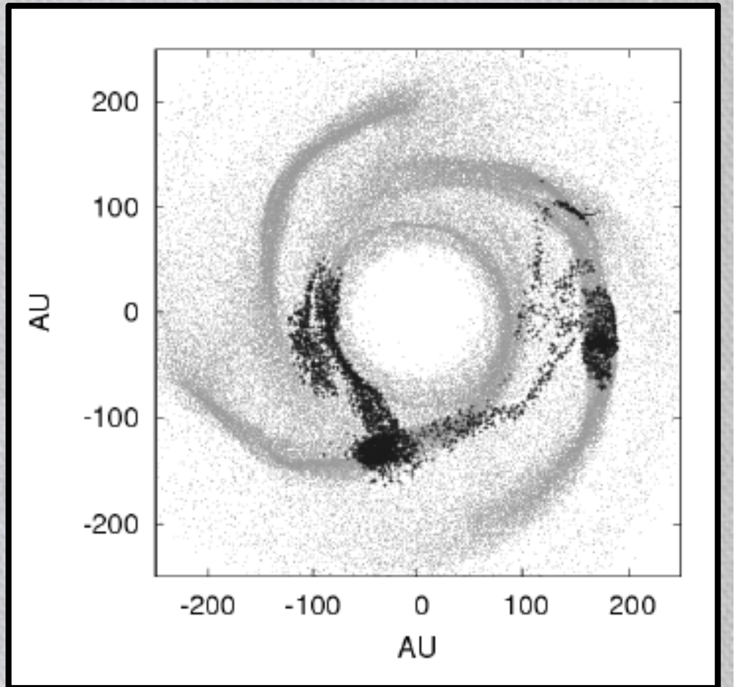


Composition

Enrichment from birth:

- High solid concentrations in spiral arms
- Clumps can be enhanced at birth by factors of ~1.5-2, if the solids are 10 cm – 100 m (**e.g. Boley & Durisen, 2010**)

Accumulation of solids where clumps form



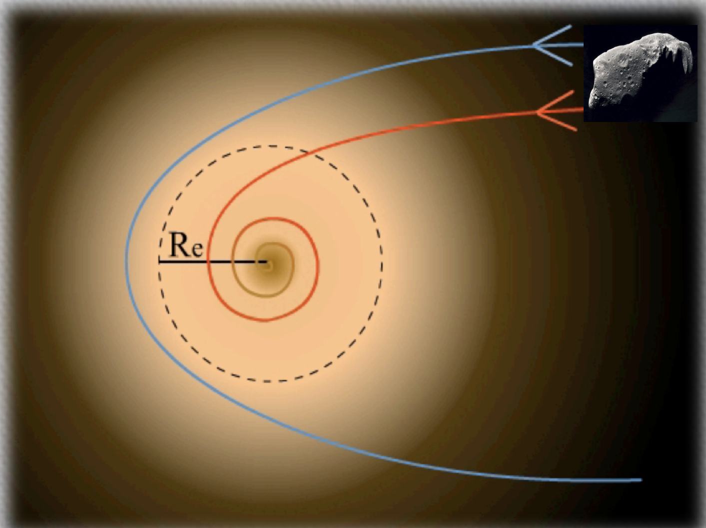
Boley et al., 2011. ApJ, 735, 30

Composition

Planetesimal Capture:

- Clumps can accrete a significant amount of solids due to gas drag
- Accreted mass (0-100 $M_{\oplus}$) depends on:

  stellar (disk) metallicity, formation location, planetary mass, planetesimal properties (size, velocity, density), disk structure



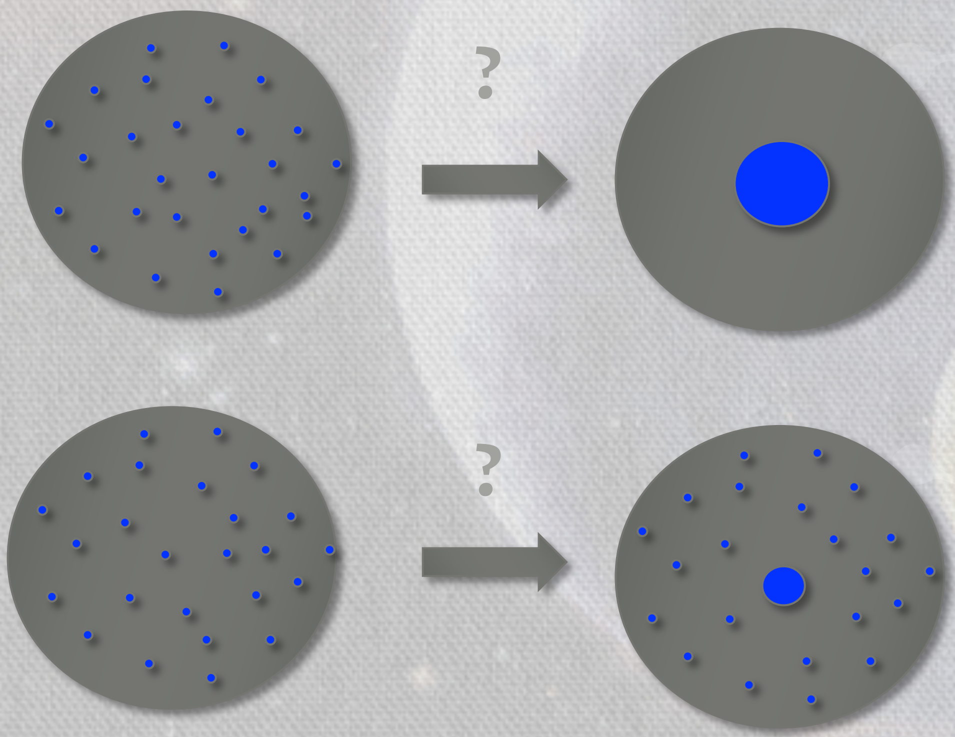
@ R. Helled

Core formation

1) Enrichment from birth (e.g., **Boley & Durisen, 2010**)

2) Grain settling (e.g., **DeCampli & Cameron, 1978**)

3) Planetesimal accretion (e.g., **Helled & Schubert, 2009**).



Gas Removal

- Clumps migrate inwards and can be disrupted at various radial distances at different evolutionary stages (**Nayakshin 2010**).

- If cores are formed and the envelope is depleted in heavy elements;

  if envelope is stripped → enriched giant planets (**Boley & Durisen, 2010; Nayakshin, 2012**)

For more details on the "*Tidal Downsizing Model*" see publications by S. Nayakshin and references therein.

Formation Models - Summary

- **Core Accretion**

Strengths:

- Fits well to the physical properties of the solar-system planets
- Can lead to a large variety of masses and compositions
- Can explain both the correlation between higher stellar metallicity and giant planet occurrence, and the heavy elements - stellar metallicity correlation
- Predicts no giant planets around low-mass and metal-poor stars
- Long formation timescale is solved by opacity reduction and/or migration

Weaknesses:

- Type-I migration
- Giant planets around metal-poor stars
- Giant planets at large radial distances

Formation Models - Summary

- **Disk Instability**

Strengths:

- Can lead to a large variety of masses and compositions
- Rapid formation
- Formation of giant planets at large radial distances
- Formation of giant planets around metal-poor stars

Weaknesses:

- Can realistic disks become gravitationally unstable?
- Even if fragmentation occurs, survival of clumps is still questionable
- Cannot naturally explain correlation between planet occurrence and stellar metallicity
- Different formation mechanism for terrestrial and giant planets

Core Accretion & Disk Instability – Complementary?

Both CA and DI could work in nature:

- Disk instability might be common in massive disk and during the disk's embedded phase (~ 10^5 yr), while core accretion occurs at later stages.

- Disk instability could represent the first trials of planet formation, which may or may not be successful. If successful, it does not preclude formation by core accretion at later stages.

- Disk instability might be necessary to explain giant planet formation around very metal-poor stars, around M-dwarfs and at very large radial distances.

- ***Overall, core accretion does explain most of the properties of solar and extrasolar planets.***

Looking Forward:

Theory:
We are entering a new stage in giant planet studies: one where we realize that in order to untangle the complex interplay of the relevant physical processes it is necessary to build even more sophisticated models that self-consistently combine these processes.

Observations:

Solar system: Juno, Cassini Solstice, future Uranus/Neptune missions

Exoplanets: Transiting giant planets at larger radial distances, more complete surveys, characterization of extrasolar giant planets (flattening/Love number, atmospheric composition, etc.)

We hope that by PPVII we will better understand planetary systems, both our own and those around other stars.

@ David A. Hardy