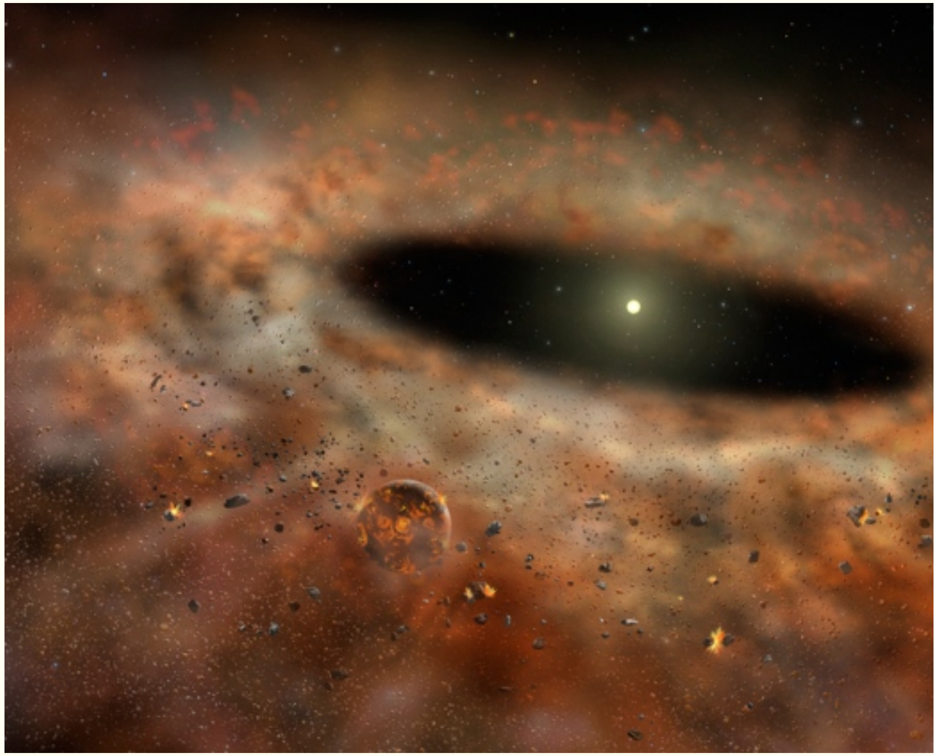
PLANET FORMATION



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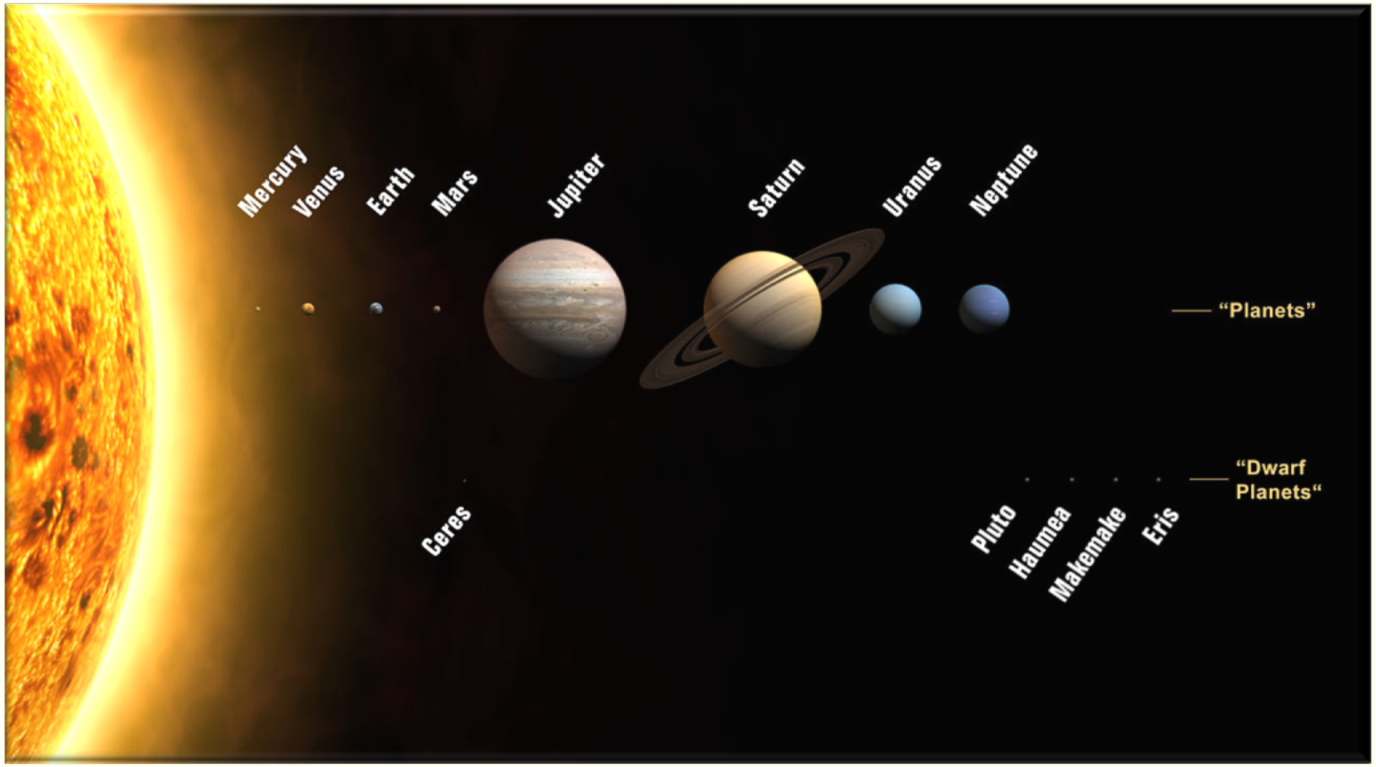
THCA
Dec 1st 2017

Outline

- **Basic concepts of planets and protoplanetary disk**
- Basic theory of planet formation
  - Core accretion
  - Gas accretion
- Summary and discussion
- References

What is planet?

- $M_\oplus = 5.972\times10^{24} g$
  $= 3.0\times10^{-6} M_\odot$
- $M_J = 1.899\times10^{30} g$
  $= 317.8 M_\oplus$
  $= 1/1047 M_\odot$



Types of planets:
- terrestrial planets
- giant planets

Mass limit:
- Upper limit: $13 M_J$
- Lower limit: ?

Fake Planet? SAD!!!

International Astronomical Union (IAU) 2006:

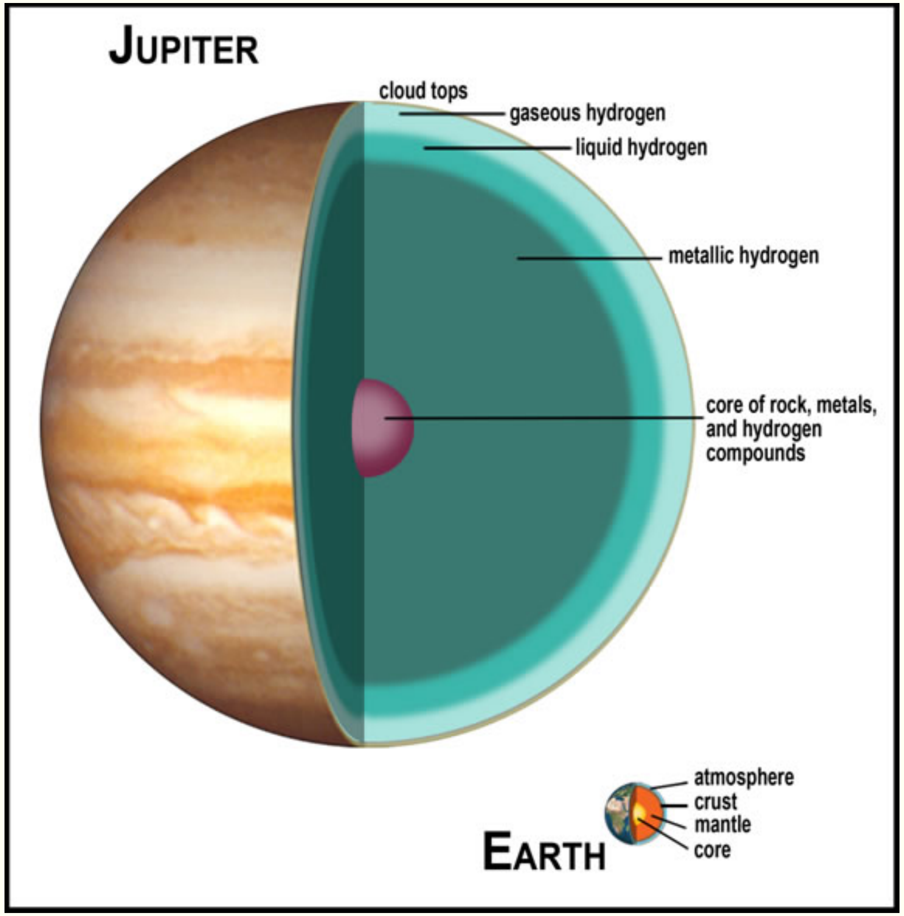
“ Clear its neighboring region of *planetesimals* ”

Terrestrial planet and giant planet

Terrestrial planet:
eg: Earth

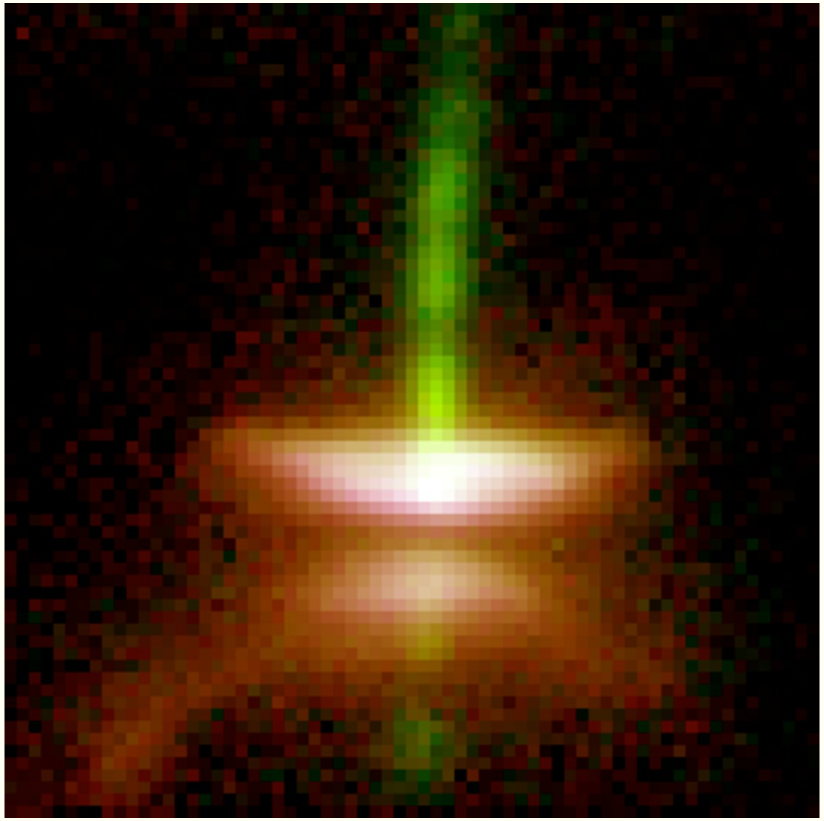
Giant planets:
- Gas giant
- Ice giant

Mean density:
- Earth: 5.514 g/cm^3
- Jupiter: 1.326 g/cm^3
- Sun: 1.41g/cm^3

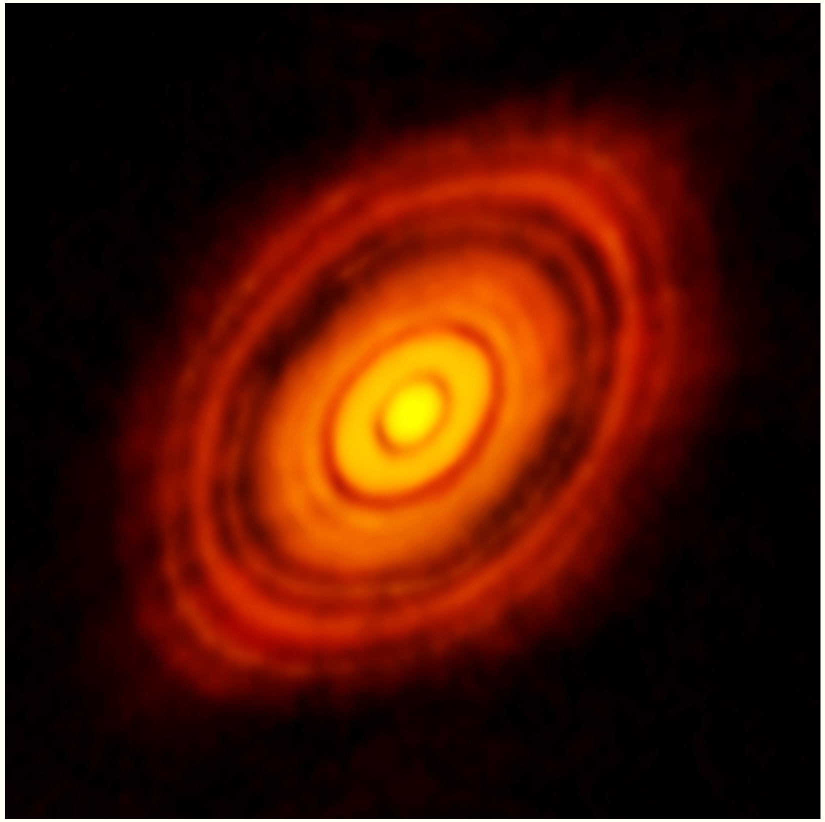


Credit: Lunar and Planetary Institute.

Protoplanetary disk: The cradle of a future planetary system



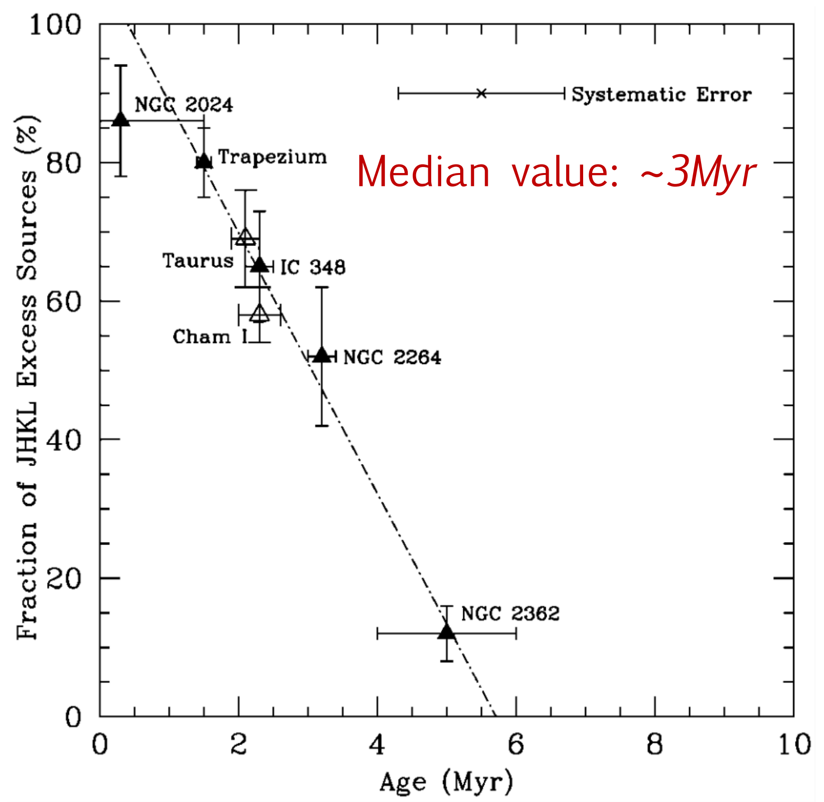
HH30, optical by HST



HL Tau, radio(mm) by ALMA

Protoplanetary disk: Basic properties

- Disk mass: ~1% of the central star
- Disk radius: a few 10s-100s AU
- Composition: gas(~99%); dust(~1%)
- **Lifetime: A few Myr**
- All with a large scatter



Haisch et al. ApJ 2001

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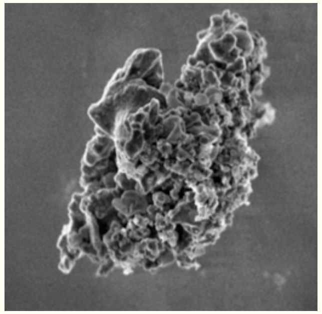
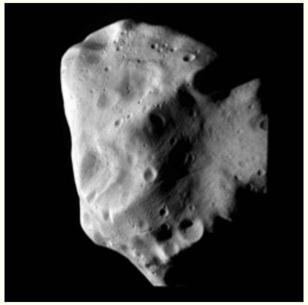
Planet formation: Stages

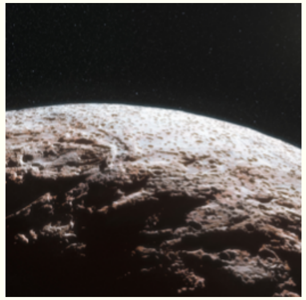


dust~μm

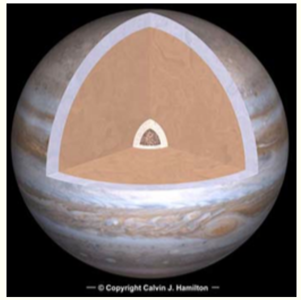
pebbles~cm



planetesimals~km



embryos~$10^3 km$



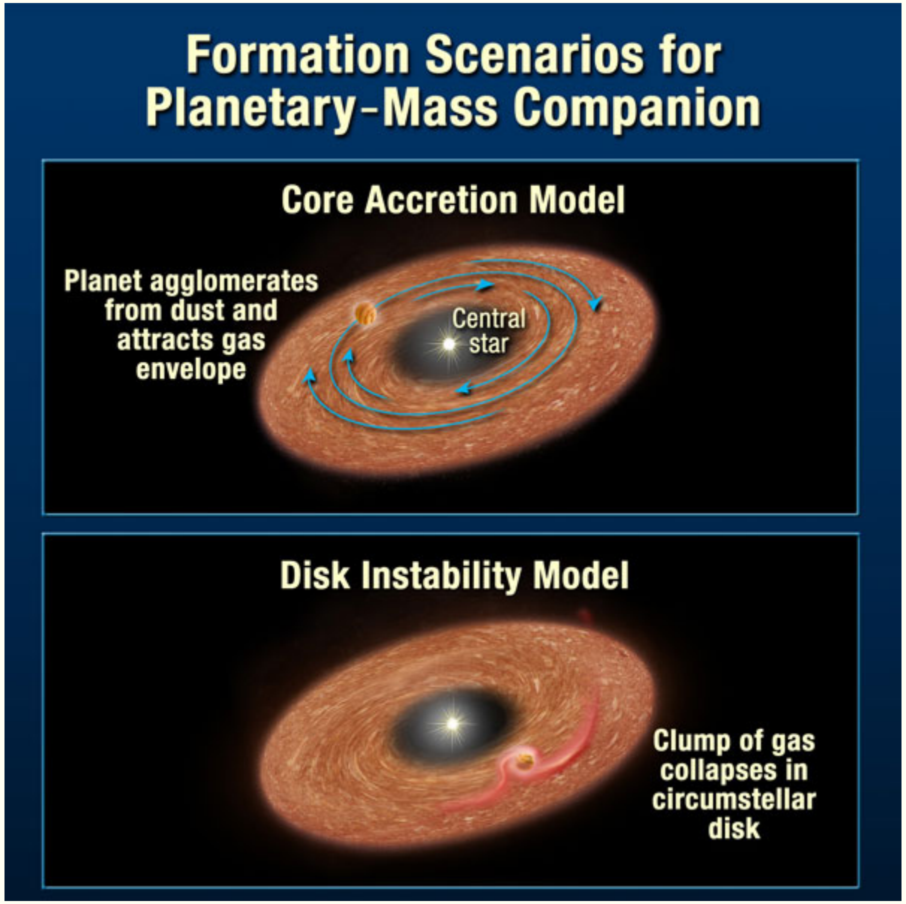
gas gaint~$10^5 km$

Grain growth	Planetesimal formation	Planetesimal growth to cores	Growth/acceration to gas giants
Sticking by surface forces	???	Gravitational accretion	

Giant Planet formation: models

- ***Core accretion model:***
  - A core of rock and ice
  - A massive envelope of gas

- Disk instability model:
  - Gravitational fragmentation of an unstable protoplanetary disk



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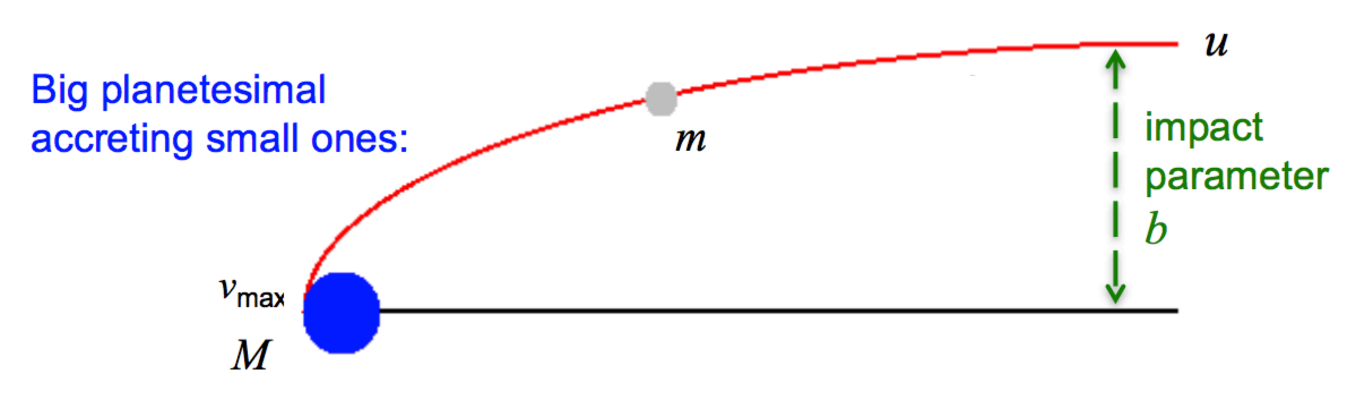
Planetesimal formation : Gravitational focusing

Two-body encounter, ignoring disk rotation



$$l = u \cdot b = u_{max} \cdot R$$

$$E = \frac{mu^2}{2} = \frac{mu_{max}^2}{2} - G\frac{Mm}{R}$$

$$\Rightarrow \quad b^2 = R^2 + \frac{2GMR}{u^2} = R^2(1 + \frac{v_{esc}^2}{u^2})$$

$$v_{esc}^2 = \frac{2GM}{R}$$

$$\sigma = \pi \mathrm{b}^2 = \pi R^2(1 + \frac{v_{esc}^2}{u^2})$$

Core accretion model

$$\sigma = \pi \mathrm{b}^2 = \pi R^2 (1 + \frac{v_{esc}^2}{u^2})$$

$$v_{esc}^2 = \frac{2GM}{R}$$

$$Collision\ rate:\ f_{col} = n\sigma u \approx \frac{\Omega\Sigma}{m}\sigma$$

$$\text{Growth}\ rate: \frac{1}{R}\frac{dR}{dt} = \frac{3}{M}\frac{d\mathrm{M}}{dt} \approx \frac{m}{M} f_{col} \approx \frac{\Omega\Sigma}{\rho R}\ (\mathbf{1} + \frac{\mathbf{v_{esc}^2}}{\mathbf{u^2}})$$

In 'cold' planetesimal disk for which $\boldsymbol{v_{esc}} \gg \boldsymbol{u}$, (suppose **u** is constant) planet will grow more rapidly: **Runaway growth**:

$$\frac{\mathbf{1}}{\boldsymbol{R}}\frac{\boldsymbol{dR}}{\boldsymbol{dt}} \propto \boldsymbol{R}$$

Once big bodies grow sufficiently massive, they can strongly **stir up** the eccentricities of neighboring small bodies $\boldsymbol{u}$ increases together with v_{esc}, : **Oligarchic growth**:

$$\frac{\mathbf{1}}{\boldsymbol{R}}\frac{\boldsymbol{dR}}{\boldsymbol{dt}} \propto \mathbf{1}$$

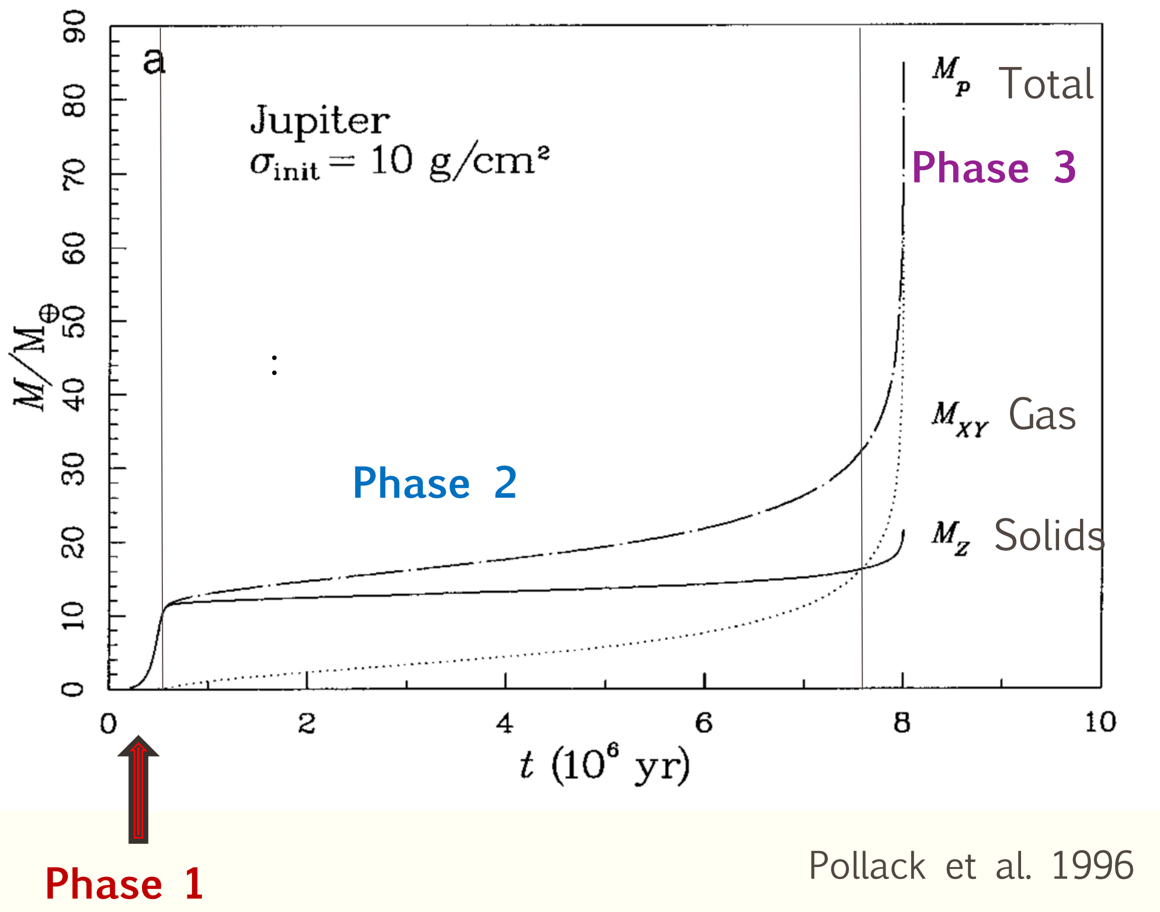
Core accretion: scenario

Phase 1: Core formation
Runaway accretion :

Ends when depleted ***feeding zone*** of planetesimals

Feeding zone: 5~10 R_H

$$R_H = a\left(\frac{M_P}{3M_\odot}\right)^{1/3}$$



Pollack et al. 1996

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Structure equation of a static atmosphere

- $\frac{dP}{dr} = -\frac{Gm}{r^2}\rho$
- $\frac{dm}{dr} = 4\pi r^2 \rho$
- $\frac{dT}{dr} = \nabla \frac{T}{P}\frac{dP}{dr}$
- $\frac{dL}{dM} = \epsilon_{acc} - T\frac{dS}{dT}$
  - ϵ:internal energy source from gas accretion, set zero ideally
  - $\epsilon_g: -TdS/dt$: gravitational contraction

Boundary conditions:

Innner: core surface

Outer: protoplanetary disk

Gas accretion model

$$\Delta m_{neb} = 4\pi R_{bd}\rho_{neb}[R_{bd} - R_p(t + \Delta t)]$$

Pollack et al. 1996

R_p: *outer envelop radius*
R_{bd}: *outer boundary* =min$[R_H,\ R_a]$

$$R_H = a(\frac{M_P}{3M_\odot})^{1/3}, \qquad R_a = \frac{GM_p}{c^2}$$

After Δt: R_{bd}↑ $(mass\ grows)$ R_p ↓ $(heat\ loss\ or\ gravity)$

Which is the dominant one???
Which accretion controls its rate of change???

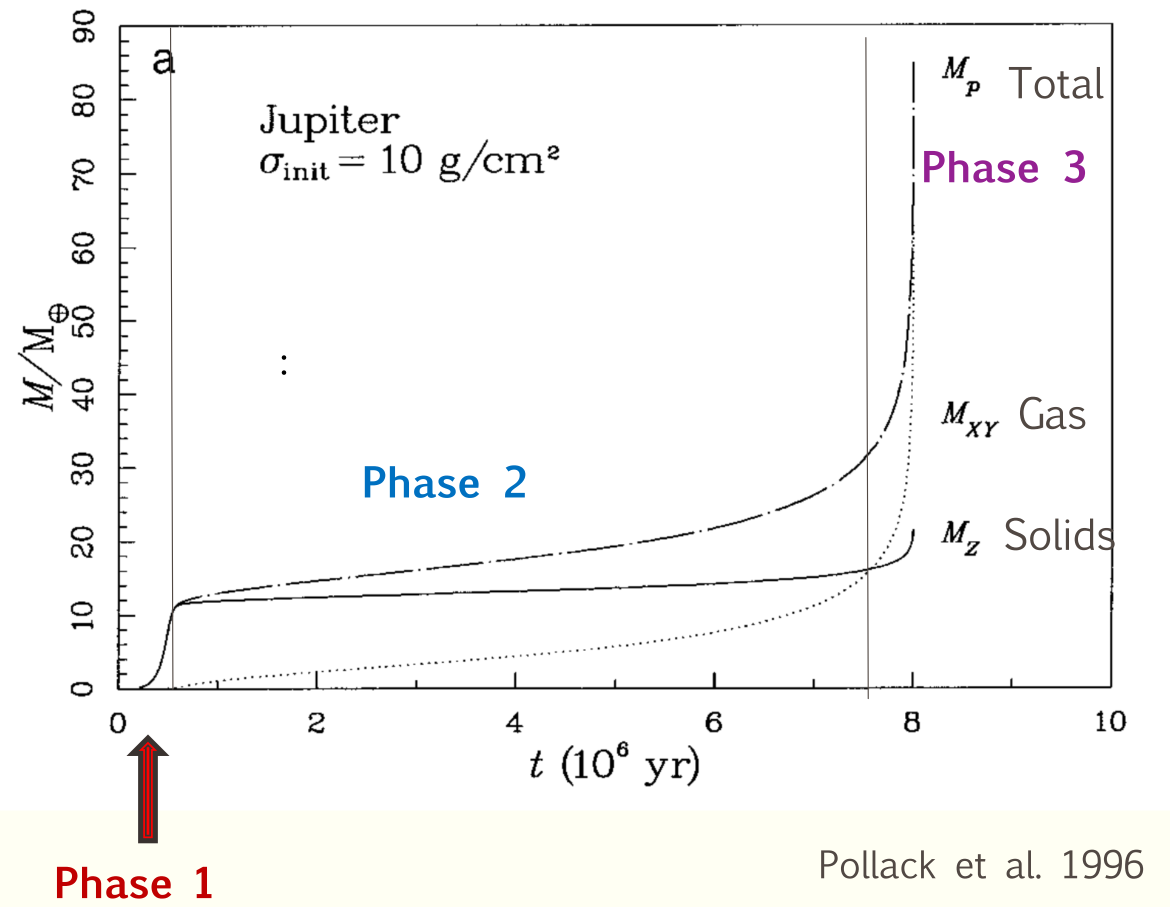
Core and gas accretion: scenario

Phase 2: Hydrostatic growth

Gas and solids
Acceration rates:
nearly constant

R_{bd} ↑ slowly since M_p grow slowly

$\boldsymbol{R_p}$ ↓ thermal considerration



Pollack et al. 1996

Gas accretion: scenario

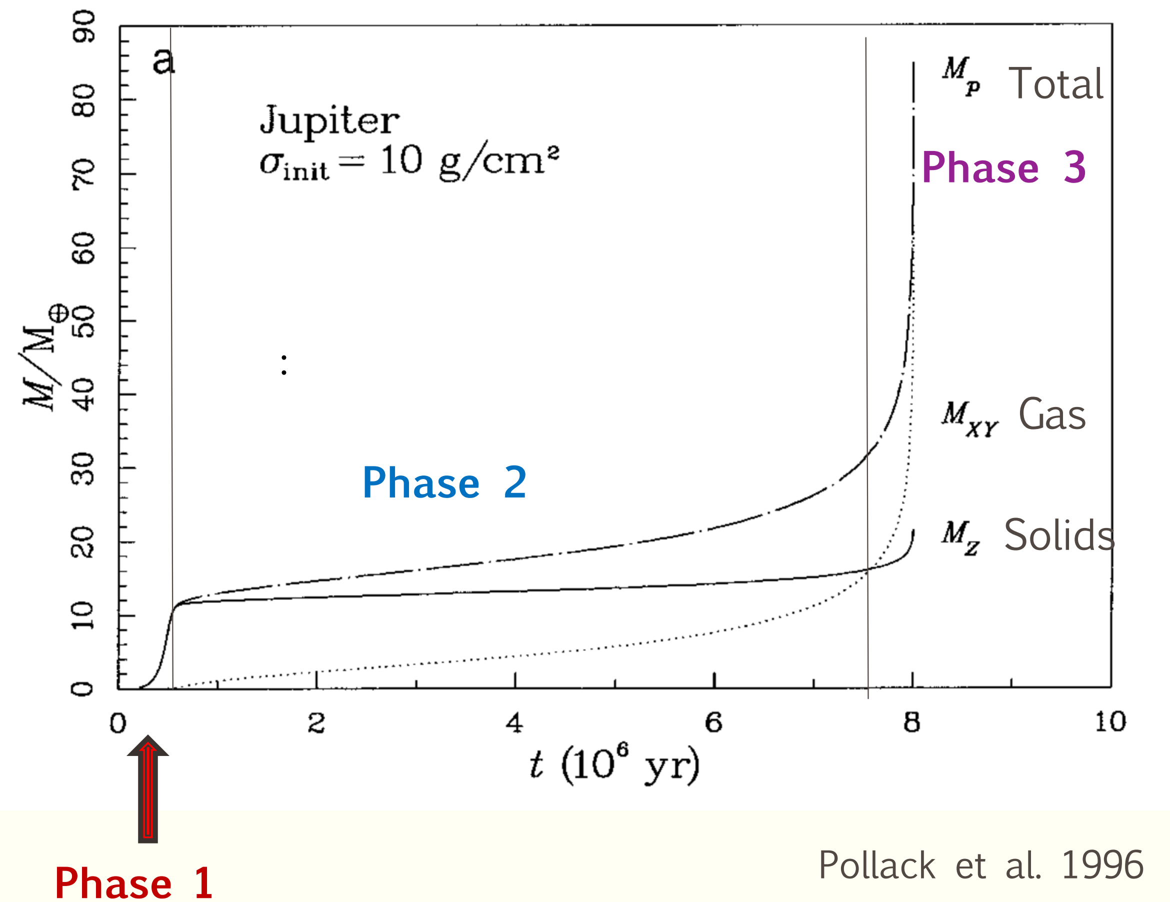
Phase 3:Gas Runaway

$\mathbf{M_{gas} \sim M_{core}}$

Trigger **runaway** accumulation of gas

$R_{bd} \uparrow$, hydrodynamic

$\mathbf{R_p} \downarrow$



Pollack et al. 1996

Critical core mass

- Runaway gas accretion generally require the solid core to reach some critical mass
- The critical core mass is often quoted to be in the range of 10-15 M_{Earth}.
- The exact value of critical core mass depends on many factors, especially on how rapidly the gaseous envelop can cool.
- Without additional heating source (e.g., heating from planetesimal accretion), the critical core mass can be as low as ~5 M_{Earth} (e.g., Piso et al. 2015).

- Giant planet formation requires the core to reach critical core mass within the lifetime of its parent protoplanetary disk.

Summary

- Background info of planet and protoplanetary disk
  - Disklife
- Gas planet formation:
  - Phase 1: Core accretion, Runaway
  - Phase 2:
    - Core accretion, Oligarchic
    - Gas accretion, Quasi-static
  - Phase 3:
    - Gas accretion, runaway

Reference

- **Pollack et al. 1996** cited by ~2100 times
- Piso et al. ApJ 2015
- Armitage, P, Cambridge Univ. Press
- Slides from Prof. Bai's homepage