Theory of Planet Formation around Low-mass or Intermediate-mass Stars

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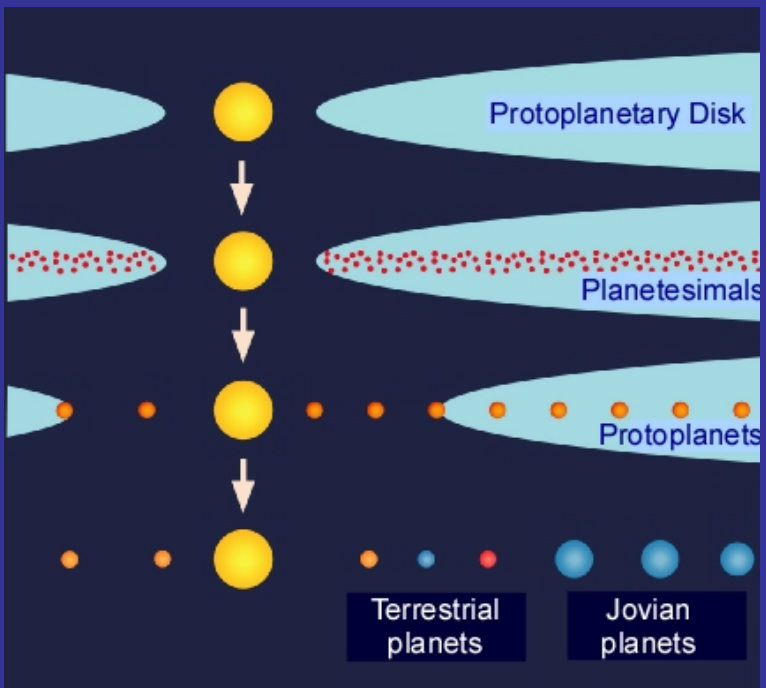
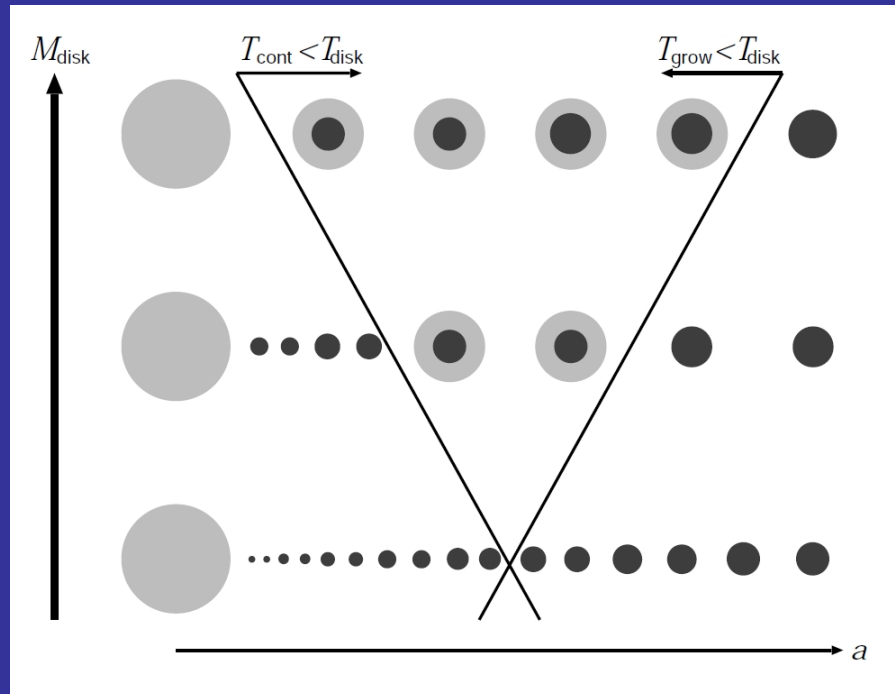
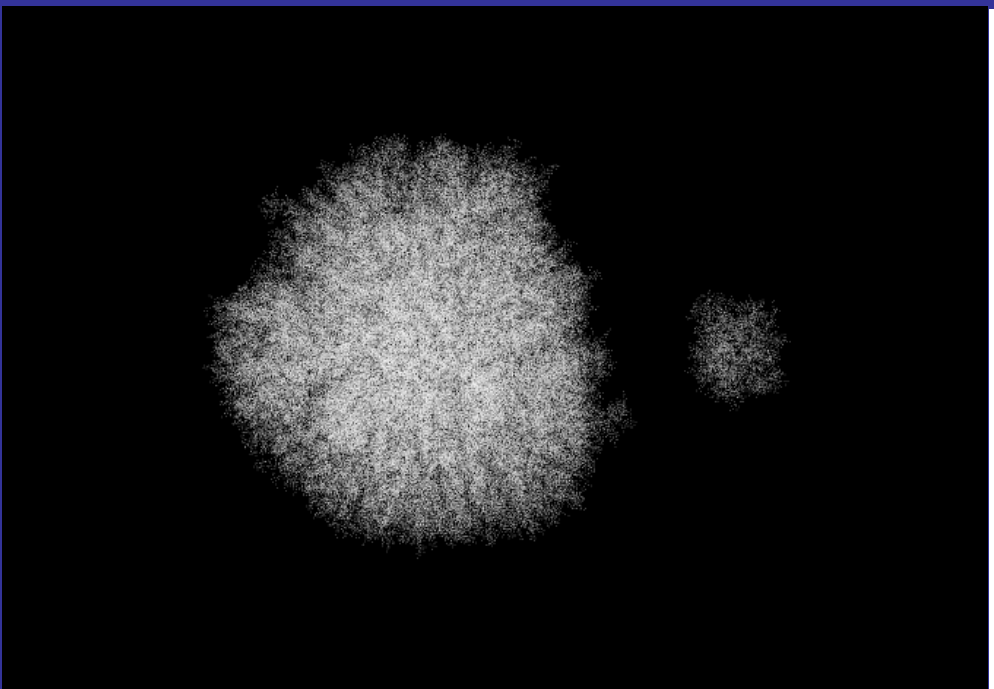


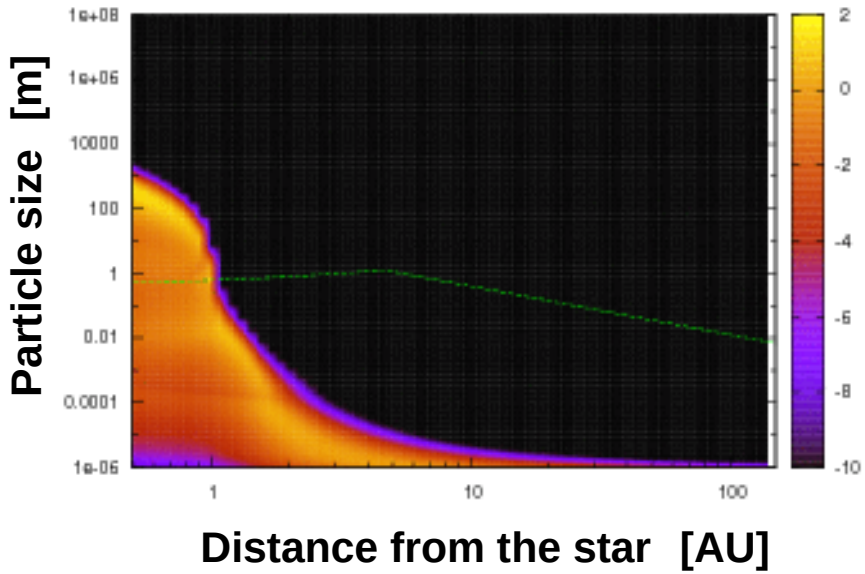


Contents

- Standard Theory of Planet Formation
- Dependence of planet formation on central stars
- Problems in Planetesimal Formation



Formation of Planetesimals from Dust



Standard Theory of Planet Formation

based on 'core accretion model'

(Kyoto group, Safronov, Wetherill…)

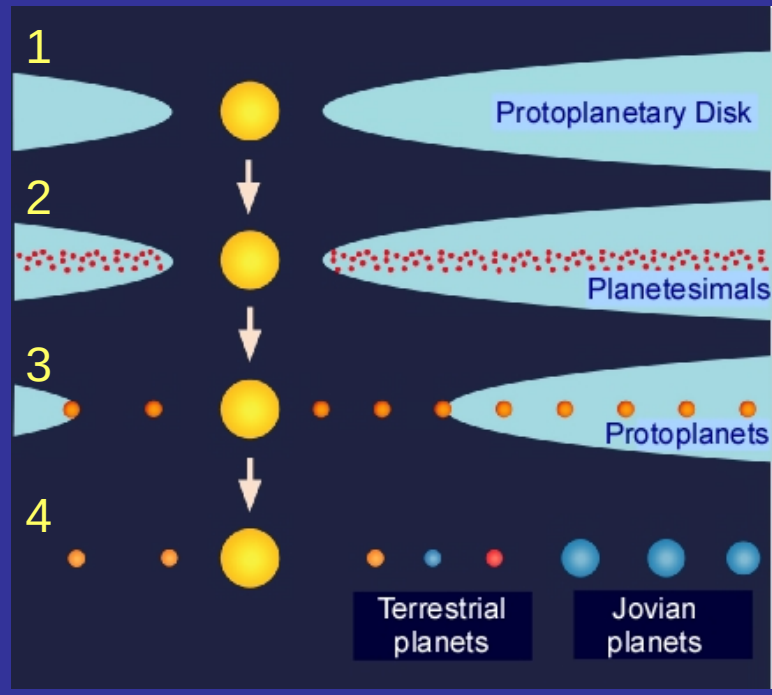
1. Formation of a protoplanetary disk

2. Thin dust layer and
   planetesimal formation

3. Accumulation of planetesimals and
   formation of protoplanets

4. - Jovian planets:
   gas capture by large protoplanets

   - Terrestrial planets:
   giant impacts between protoplanets

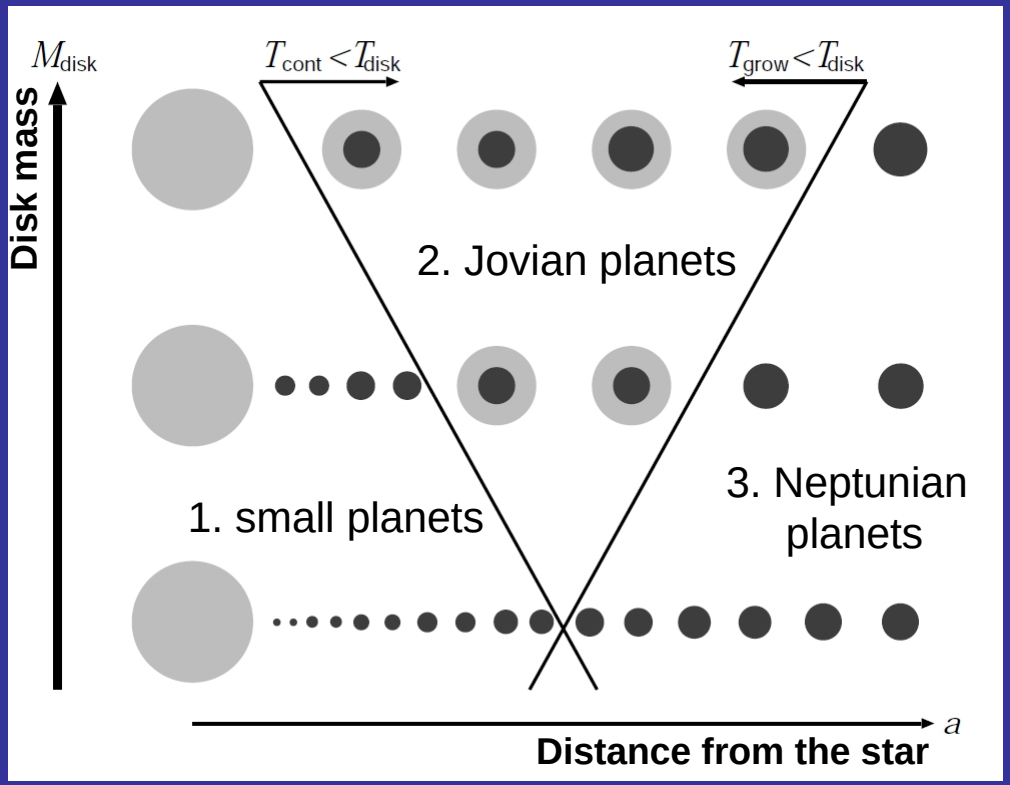


Problems:
- planet migration
- planetesimal formation

Diversity of Planet Systems in various disks

(Kokubo and Ida 2002)

A massive disk produces many Jovian planets.



Region 1: small planets (insufficient solid material)

Region 2: Jovian planets

Region 3: planets without gas (Neptunian planets due to slow growth)

Dependence of planet formation on central stars

Effect of the central star

- Mass of the central star … weak dependence (see below)
- Disk temperature, life time, metallicity

Growth Time of planet

$$T_{\rm grow} \sim \frac{a^2 \Omega_{\rm K}}{G R_{\rm p} \Sigma_{\rm solid}} \left(\frac{M_{\rm p}}{M_{\rm star}} \right)^{2/3} \propto a^{1/2} \, \Sigma_{\rm solid}^{-1} \, M_{\rm star}^{-1/6}$$

$M_{\rm star}$: star mass, $M_{\rm p}$, $R_{\rm p}$: planet mass, radius, a : orbital radius,
$\Omega_{\rm K}$: Keplerian angular frequency, $\Sigma_{\rm solid}$: solid surface density

Final proto-planet mass (core mass)

$$M_{\rm p} \propto a^3 \, \Sigma_{\rm solid}^{3/2} \, M_{\rm star}^{-1/2}$$

Dependence of planet formation on central stars

Disk Temperature (passive disk)

$$T_{\text{disk}} \propto L_{\text{star}}^{1/4} \propto M_{\text{star}}^{1\ldots}$$

- Snow line goes outward in the disk for intermediate-mass stars.
  ex: $M_{\text{star}} = 2M_{\text{solar}}$ → $a_{\text{snow}} \sim 15\text{AU}$
- Jovian planets would have rocky cores around intermediate-mass stars.

Disk Life Time

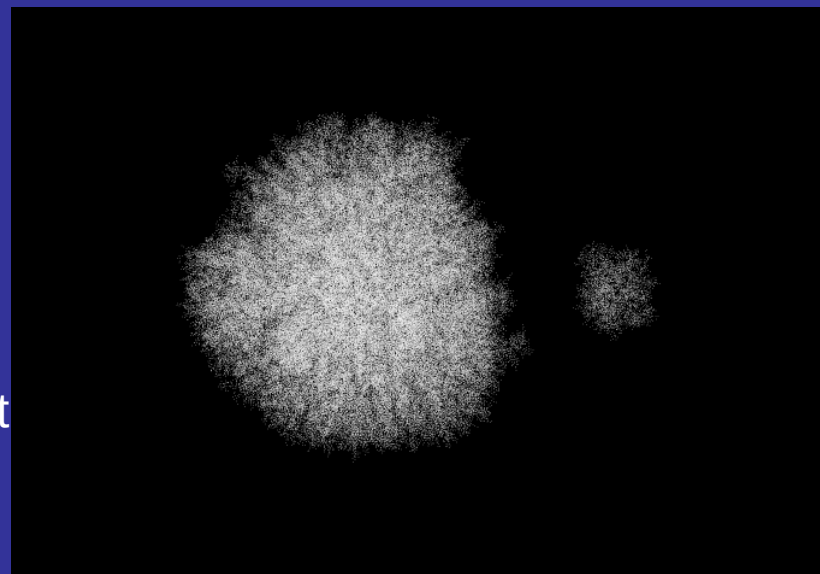
Disks around intermediate-mass stars would have short life time.

→ Difficulty in formation of Jovian planets outside of the snow line.

Problems in Planetesimal Formation

- Planetesimal formation is the most uncertain part of the planet formation process.
  - Gravitational instability is easily prevented by weak ‘wind’ (~10cm/s) in the gaseous disk.
  - The m-sized particles quickly fall to the central star.

- Planetesimal formation through direct dust growth
  - Icy dust easily stick!



Numerical simulation of a collision of icy dust
(The impact velocity is 90 m/sec!)

Planetesimal Formation by Direct Dust Growth

Brauer et al. (2007)

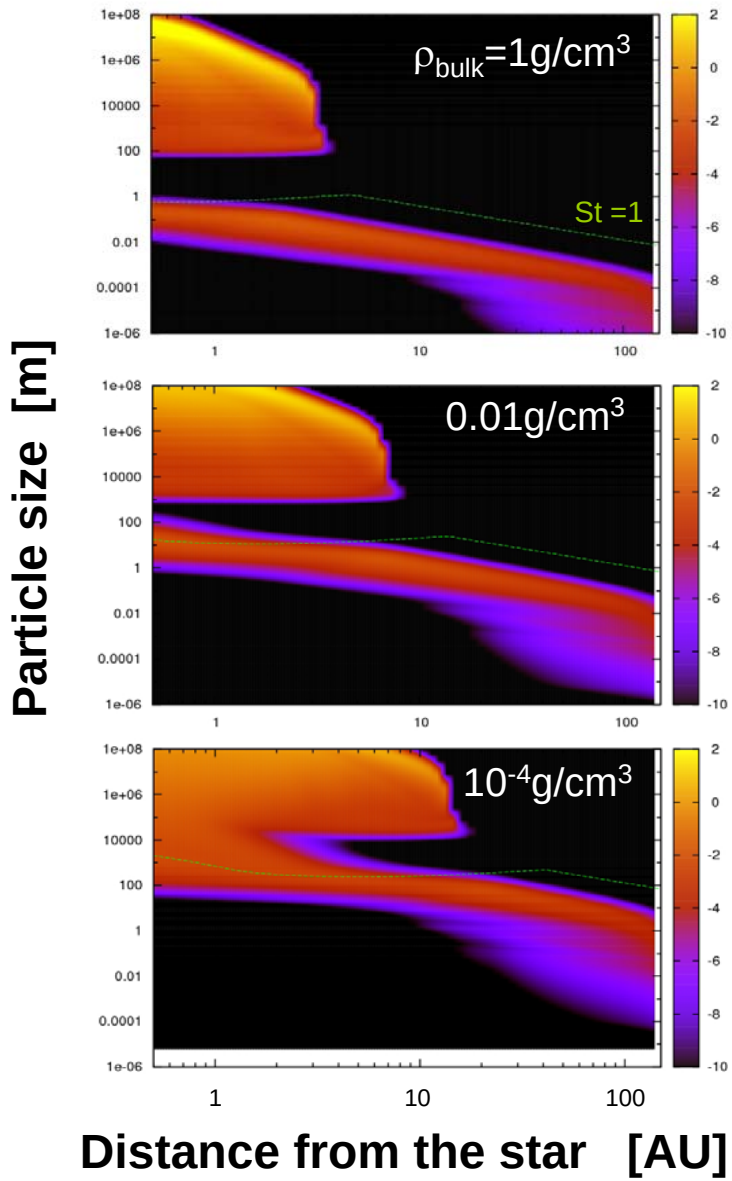
Planetesimals can be formed by direct dust growth only at inner disk with R<2AU.

Our calculation (*Tanaka et al.* in prep.)

- Icy aggregates can grow without disruption.
- Low-density dust makes the planetesimal-forming region wider (up to 10AU).
- The surface density of the solid component is significantly enhanced in the planetesimal-forming region due to dust infall.

Making planetesimals beyond 10AU is difficult!

→ Icy planetesimals would not form around intermediate-mass stars



Summary

1. Planet formation is dependent on the disk mass but almost independent on the mass of the central star.

2. The snow line is located at ~ 15AU in the disk for intermediate stars.

3. Around intermediate-mass stars, Jovian planets would be formed inside of the snow line and they have rocky cores.

4. Icy planetesimal would not be formed around intermediate-mass stars.