Planetary Formation Scenarios Revisited: Core-Accretion versus Disk Instability

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What's New?

- **Different conditions for gas giants formation**
  → **Metallicity of a disk, Planet Mass, Disk Mass**

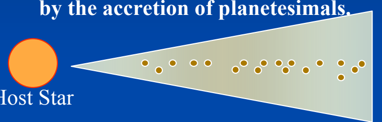
- **Dependence of the disk metallicity on dust and gas surface density**
  → $[Fe/H] \approx \log_{10}\left(\frac{f_d}{f_g}\right)$ $f_{d(g)}$:The scaling factor for the dust (gas) surface density of the Minimum Mass Solar Nebulae model ($f_{d(g)} = 1$)

Planetary Formation Scenarios

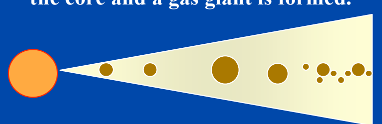
Core-Accretion

(e.g. Safronov 1969; Hayashi et al. 1985; Pollack et al. 1996)

1. Heavy element cores are built by the accretion of planetesimals.



2. Rapid gas accretion occurs onto the core and a gas giant is formed.

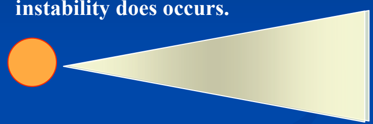


3. Gas dissipates from a disk. (The gas depletion timescale: 10^7yrs)

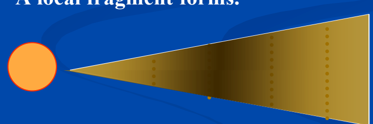
Disk Instability

(e.g., Kuiper 1951; Cameron 1978; Boss 1997)

1. If a disk is sufficiently massive, the disk instability does occurs.



2. The entire disk is global instable. A local fragment forms.



3. Such clumps contract to form giant gaseous protoplanets.

The Region Where Gas Giants Are Formed By Core-Accretion (CA-Region)

The Conditions For Gas Giant Formation

(1) The core mass increases over the critical core mass before the disk gas dissipates

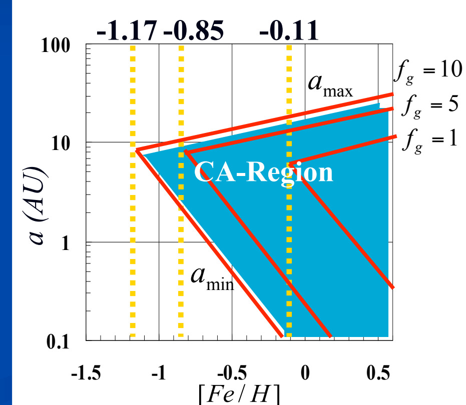
$$\tau_{c,acc} \le \tau_{disk}$$

$$a \le a_{\max} = 7.4 \times f_g^{\frac{14}{27}} 10^{\frac{27}{10}[Fe/H]}$$

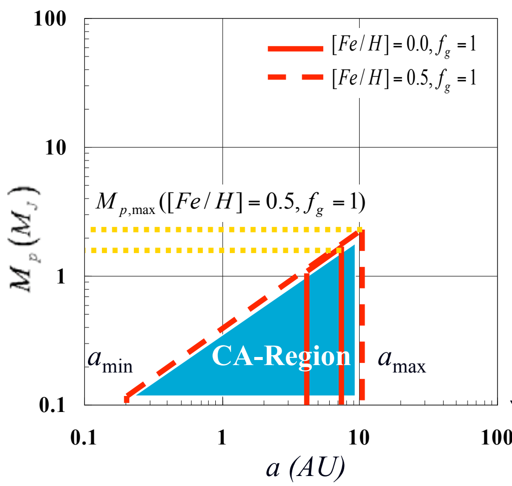
(2) The core isolation mass is larger than the critical core mass:

$$M_{c,iso} \ge M_{c,crit}$$

$$a \ge a_{\min} = 4.1 \times f_g^{-2} 10^{-2[Fe/H]}$$



Upper Limits For Planet Mass In Core-Accretion Model



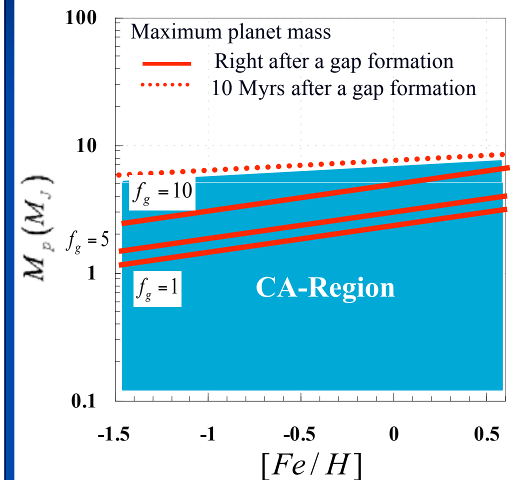
Gas Giants Formation Scenario

***Heavy element cores are built by the accretion of planetesimals.**

*** When core mass is higher than critical core mass, gas accretes rapidly onto the core.**

*** When the gravitational scattering is equal to pressure gradient and viscous diffusion, a gap is formed.**

Upper Limits For Planet Mass In Core-Accretion Model

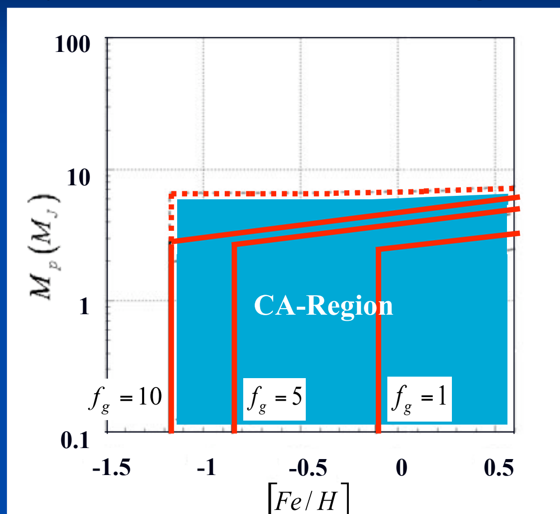


Evolution of protoplanet after a gap formation

*** During the protoplanet is embedded in the accretion disk, gas around the gap is accreted onto the protoplanet**

*** The planet mass increases until gas dissipates from the disk (~10Myr)**

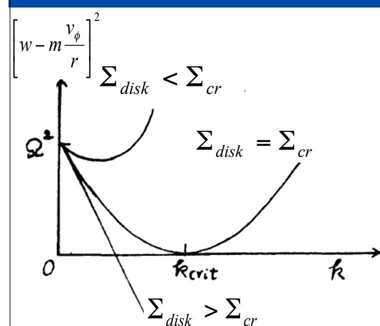
The Region Where Gas Giants Are Formed By Core-Accretion (CA-Region)



Planetary Formation By Disk Instability

(e.g. Kuiper 1951; Cameron 1978; Laughlin & Bodenheimer 1994; Boss 1997)

- **When self-gravity of a disk is stronger than tidal force and gas pressure (Q < 1), the disk instability occurs.**
- **When a spatial scale of a perturbation equals to the critical wavelength: Q ~ 1 the fragment mass is minimum one.**

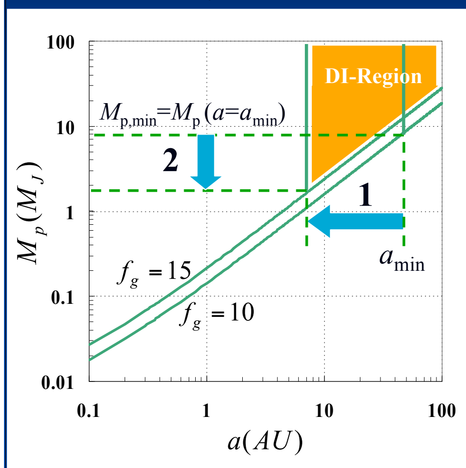


Toomre-Q (Toomre 1964)

$$Q = \frac{\Sigma_{crit}}{\Sigma_{disk}} \approx \frac{c_s \Omega_{ep}}{\pi G \Sigma_{disk}} \propto f_g^{-1} \cdot T^{\frac{1}{2}} \cdot M_*^{\frac{1}{2}}$$

*When Q is less than 1, self-gravity of a disk is stronger than tidal force and gas pressure.
*The range where the disk instability occurs (DI-Region) is determined by the **disk temperature** and **the gas surface density**

The Region Where Gas Giants Are Formed By Disk Instability (DI-Region)



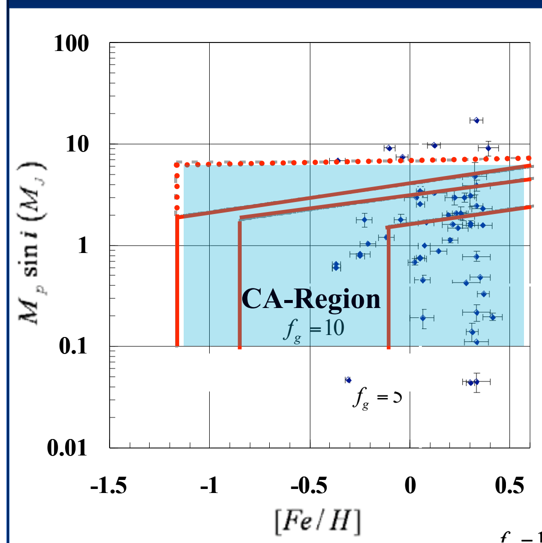
The dependence of the minimum planet mass formed by disk instability on the semi-major axis

1. As the gas surface density of the disks increases, the DI-Region **widens inwardly**.

2. As the gas surface density of the disks increases, **the lower limits for the planet mass decrease.**

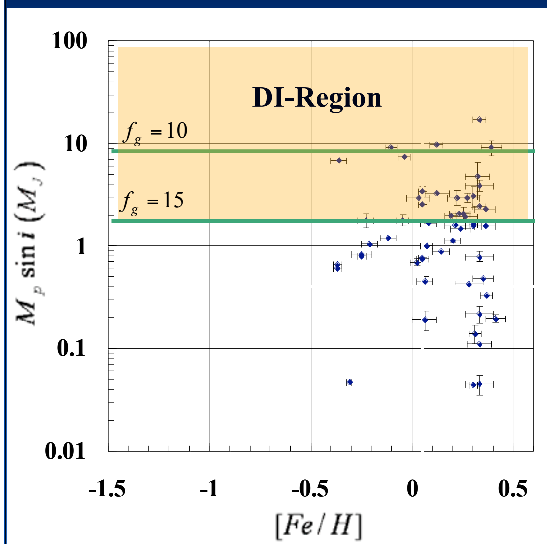
The reason is that, as the region is nearer the host star, the gas pressure is higher and the gravitation of the host star is stronger.

Core-Accretion vs. Disk Instability (G-type stars: 60)



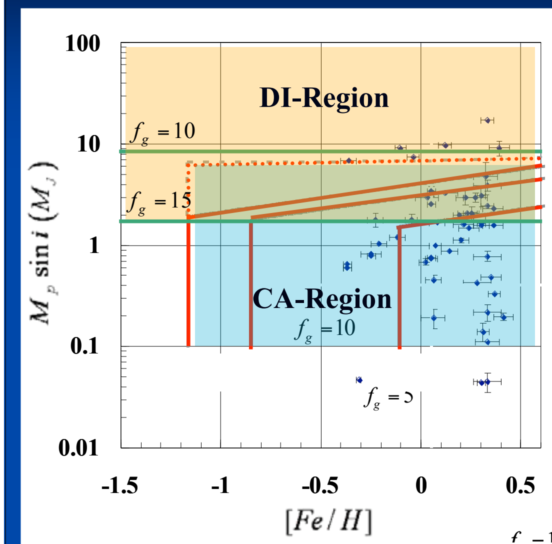
* **Core-Accretion model has the upper limits for planet mass and the lower limits for metallicity of the disk.**

Core-Accretion vs. Disk Instability
(G-type stars: 60)



* Disk Instability model has the **lower limits** for planet mass.

Core-Accretion vs. Disk Instability
(G-type stars: 60)



* 90% (54/60) of the planets detected so far occur in the region where the gas giants can be explained by the core-accretion model.

* The rest 10% can only explained by the disk instability model.

Conclusions

- **We derived the conditions for metallicity of the disks and planet mass for gas giant formation** using the core-accretion model and the disk instability model. we checked whether the planets detected (161 cases) so far satisfy the above conditions.
- **90% of the planets detected occur in the range where gas giants can be explained by the core accretion model. The rest 10% can only explained by the disk instability model, not by the core-accretion model, in case that migration is not considered.**