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

\[
[Fe/H] = \log_{10} \left( \frac{f_d}{f_g} \right) \cdot f_{d(g)}
\]

(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., Saito 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: 10^7 yrs)

Disk Instability
(e.g., Kuiper 1951; Cameron 1978; Boss 1997)
1. If a disk is sufficiently massive, the disk instability does occur.
2. The entire disk is global unstable. 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
   \[ \tau_{c,acc} \leq \tau_{disk} \]
   \[ a \leq a_{max} = 7.4 \times f_g^{27} 10^{10} \text{[Fe/H]} \]
2. The core isolation mass is larger than the critical core mass:
   \[ M_{c,iso} \geq M_{c,crit} \]
   \[ a \geq a_{min} = 4.1 \times f_g^{27} 10^{2} \text{[Fe/H]} \]
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.*

**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: $Q \sim 1$ the fragment mass is minimum one.

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Toomre-Q (Toomre 1964)

$$Q = \frac{\Sigma_{\text{crit}}}{\Sigma_{\text{disk}}} = \frac{c_s \Omega_{\text{ep}}}{\pi G \Sigma_{\text{disk}}} \propto f_{\text{g}}^{-1} \cdot T^{-\frac{3}{2}} \cdot M_s^{-\frac{1}{2}}$$

*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)

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.

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

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.

* 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 be 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 be explained by the disk instability model, not by the core-accretion model, in case that migration is not considered.