Gap structure around planets in protoplanetary disks

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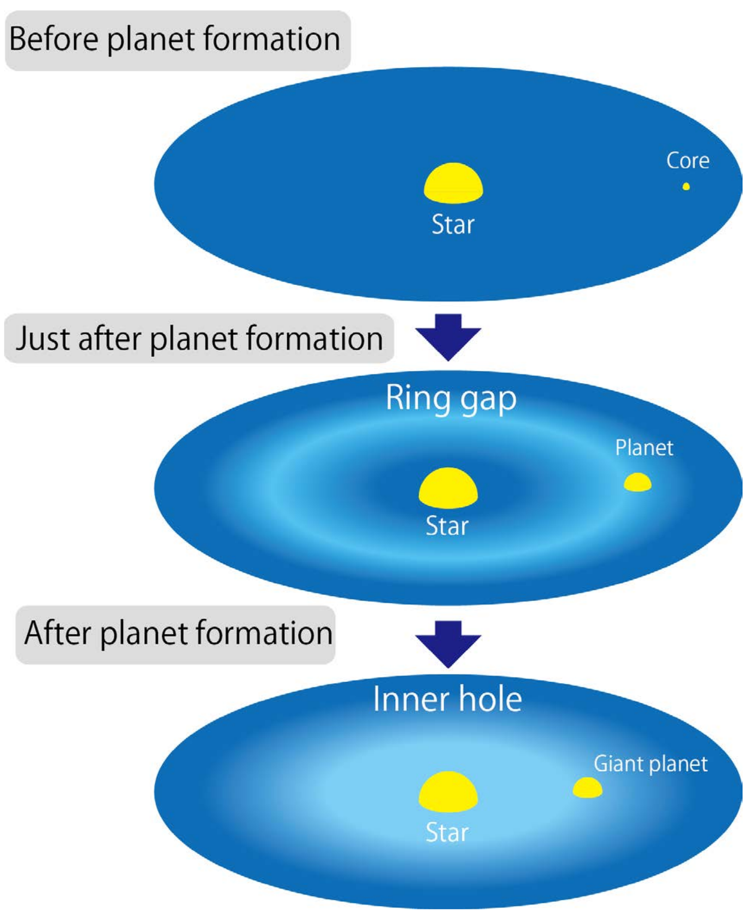
INTRODUCTION

By recently observation for protoplanetary disks, transitional disks with the inner hole and pre-transitional disks with gaps are discovered.

The gap formation by the giant planet is one of possible mechanism for the transitional disk and pre-transitional disk.



The planet creates the gap by the gravitational interaction with the disk gas around it.

How large planet is needed to create a deep gap ?

- ✓Planet mass growth
- ✓Planetary migration
- ✓Disk evolution (Inner hole formation)

1D model

Basic equation

Assumptions

- Steady state
- No gas accretion onto the planet
- Local approximation in the vicinity of the planet

Angular momentum flux

$$j\dot{M} - 2\pi R^3 \Sigma \nu \frac{d\Omega}{dR} = F_J^\infty - \int_R^\infty 2\pi R' \Sigma \Lambda dR'$$

or

$$-\frac{d}{dR}\left(2\pi R^3 \Sigma \nu \frac{d\Omega}{dR}\right) = 2\pi R \Sigma \Lambda$$

F_J^∞ Angular momentum flux without a planet

$\dot{M}$ Mass flux

h Disk scale height

Torque density deposited by density waves

$$\frac{dT}{dR} = 2\pi R \Sigma \Lambda$$

Λ indicates the torque density per unit mass

Differential of angular velocity is not the Kepler velocity !

Disk rotation law

Radial forces balance

$$R^2\Omega = \frac{GM_*}{R^2} + \frac{1}{\Sigma}\frac{dP}{dR}$$

Gap width

$$l \approx \left(\frac{d\ln\Sigma}{dR}\right)^{-1} \sim h$$

Angular velocity

$$\Omega \simeq \Omega_K\left[1 + \boxed{\frac{h^2}{R}\frac{d\ln\Sigma}{dR}}\right] \qquad \sim O(h/R)$$

Difference of angular momentum

$$\frac{d\Omega}{dR} \simeq \frac{3}{2}\frac{\Omega_K}{R}\left[1 - \boxed{\frac{h^2}{3}\frac{d^2\ln\Sigma}{dR^2}}\right] \qquad \sim O(1)$$

The disk rotation law is sufficiently altered by the radial pressure gradient !

Rayleigh criterion

If the angular velocity is much altered, the structure becomes unstable !

Stable condition (Rayleigh criterion)

$$\frac{dj}{dR} \geq 0, \qquad j = R^2\Omega$$

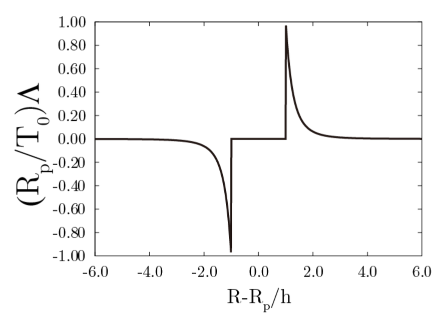
(Tanigawa&Ikoma 2007)

Gravitational torque density

The torque distribution deposited in the disk is a difficult problem associated the wake and dump of the density waves.

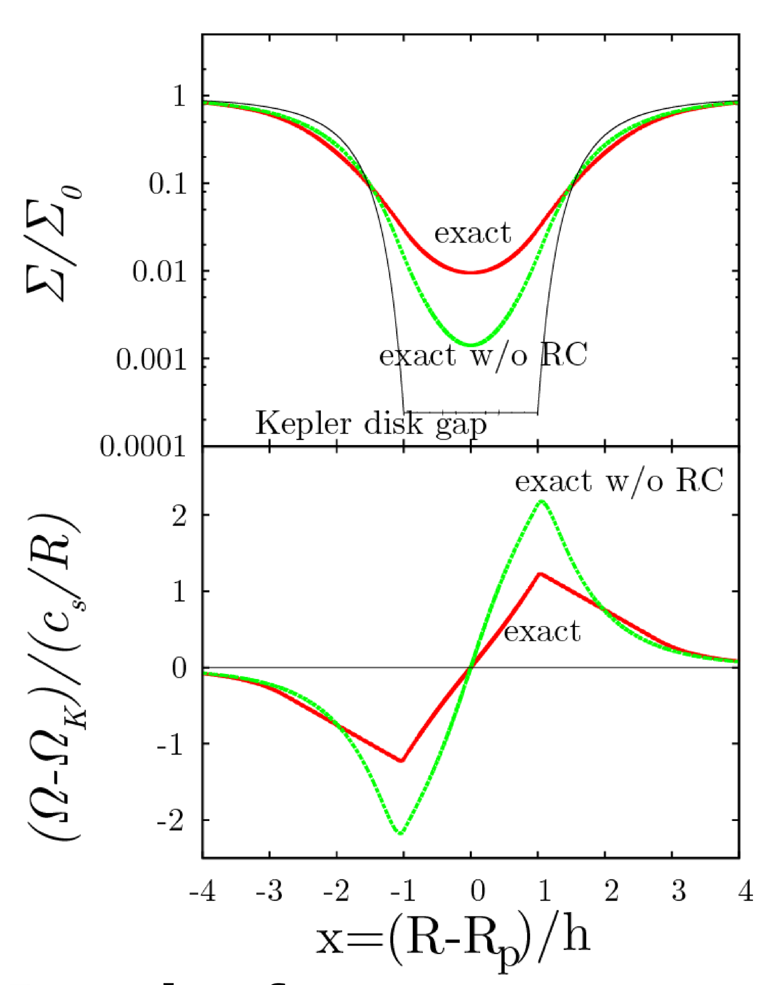
Thus, we use a following toy model;

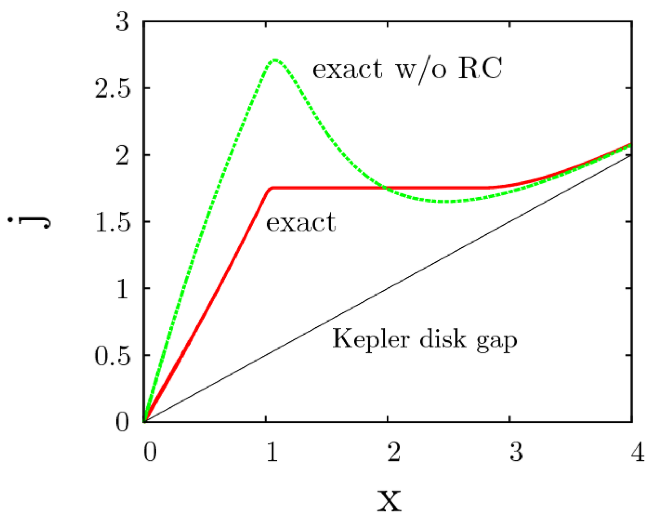
$$2\pi R\Lambda = \frac{1}{\Sigma}\frac{dT}{dR} = \begin{cases} \frac{T_0}{R_p}(R-R_p)^{-4} & (|R-R_p| > h), \\ 0 & (|R-R_p| < h). \end{cases}$$



RESULT

Gap structure $M_p = 20M_\oplus,\ H = 1/30,\ \alpha = 10^{-3}$

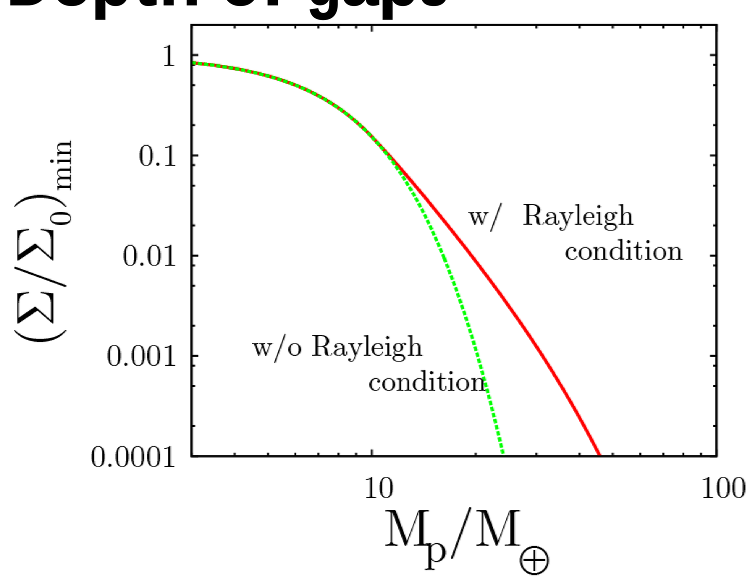




By the change of disk rotation law, the gap structure becomes smooth and the depth get shallower.

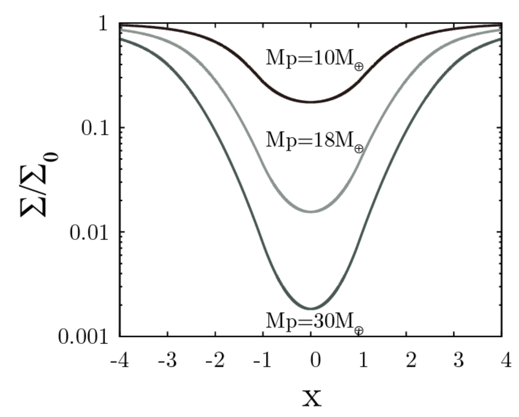
In addition, the depth of gap becomes more shallower due to the Rayleigh condition.

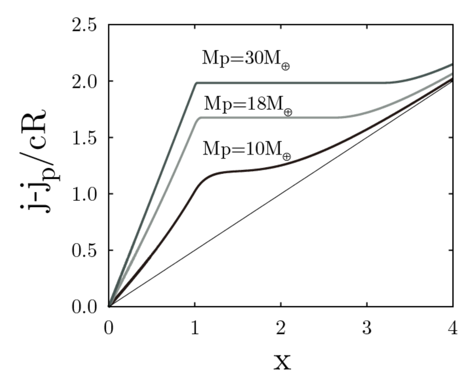
Depth of gaps



The depth of gaps for exact solutions with the Rayleigh condition, exact solutions without the Rayleigh condition and the solutions with the Kepler rotation.

The depth of gap is determined by not only the viscosity and planet torque, but also the angular velocity profile and the Rayleigh condition.



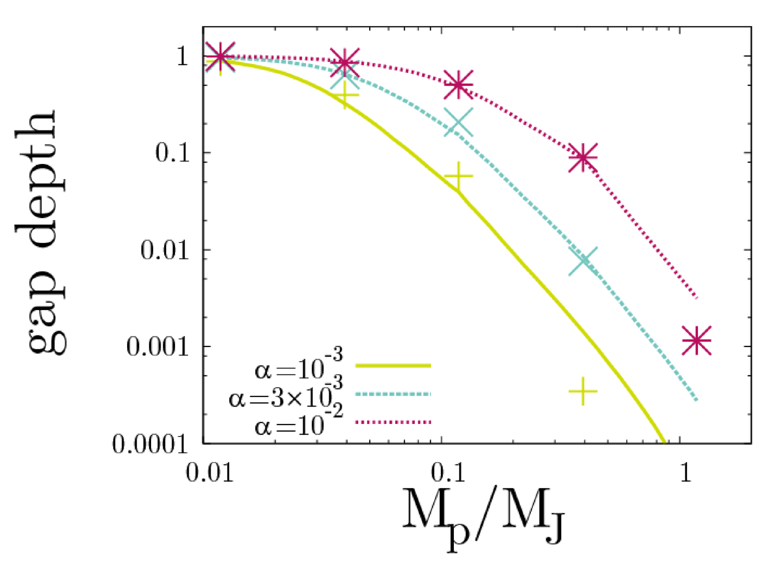


The surface density profile (left) and specific angular momentum distribution (right) for various planet masses.

The Rayleigh condition acts effective for massive planet.

Comparison with 2D numerical fluid simulation

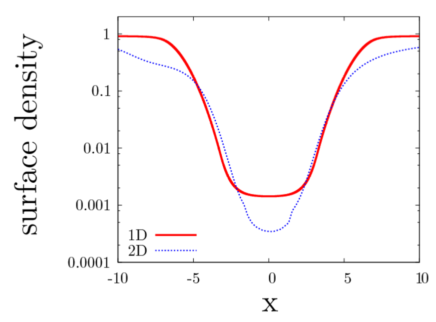
We also demonstrate 2D numerical fluid simulation using FARGO. We compare the results of 1D model and 2D simulation, varying the torque model and the critical condition of the Rayleigh instability. As a result, we find that the gap profile of 2D indicates the concentrated torque distribution.

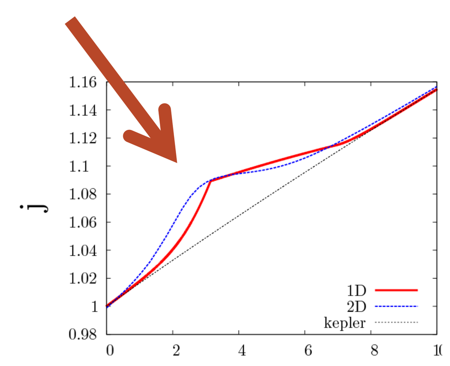


Lines are results of 1D model, and Points are results of 2D simulations

The region where the specific angular momentum is different from the Kepler velocity is very narrow.

It indicates that the planet torque is spread in narrow field.





The surface density(left) and the specific angular momentum (right) for $0.4M_J$, H=1/30 and $\alpha=10^{-3}$.

Summary

- Using the 1D disk model, we obtain the surface density profile and angular velocity distribution in the gap.
- The difference of angular velocity is much changed that the Rayleigh criterion is broken.
- Since the Rayleigh condition controls the surface density gradient, the decrease of bottom surface density is prevented.
- Our model can reproduce precisely results of the 2D simulations for wide range of the planet mass and disk parameters.