Can gap suppress gas capturing growth of giant planets?

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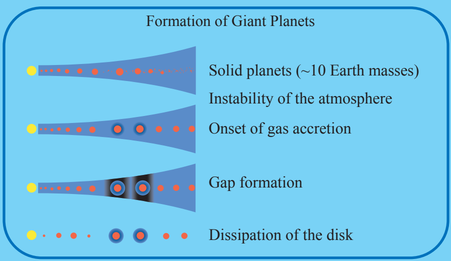
Abstract

We study the final masses of giant planets growing in a protoplanetary disk by using a toy model, which employs simulation-based two empirical formulae for gap depth and accretion rate of area of protoplanetary disks. We find that gap opening is not effective to suppress gas capturing growth of giant planets: a Jupiter-mass planets are easily formed even in the case with small disk surface density (1/20 of the standard (MMSN) disk model. Since such a light disk is necessary for Jupiter-mass planets, type I migration can be mitigated, which might save protoplanets from infall onto the central star. Hot jupiters, which are thought to be formed outer region and then move inward by type II migration, could be formed in-situ (at 0.1 AU for example).

Introduction



Key question: When does the planetary growth stop?

Can gap really stop gas accretion onto the planets?

"Classical" two conditions for gap opening:

"Thermal condition" $M_p > 3\left(\frac{h}{r_p}\right)^3 M_*$ "Viscous condition" $M_p > \left(\frac{40\nu}{r_p^2\Omega_p}\right)^3 \left(\frac{h}{r_p^2}\right)^{3/2} M_*$

Are these mass really good estimations for the mass of giant planets?

Purpose of this study

To investigate final mass of giant planets by a toy model that simulates long term evolution of planetary growth of giant planets by modeling gas accretion rate onto planets semi-analytically.

Methods

Disk model

Self-similar viscous evolution:

$$\Sigma_{\rm ss} = \frac{M_{\rm d,ini}}{2\pi R_{\rm o}^2}\left(\frac{r}{R_{\rm o}}\right)^{-1} \tilde{t}_{\rm ss}^{-3/2} \exp\left(-\frac{r/R_{\rm o}}{\tilde{t}_{\rm ss}}\right),$$

$$\dot{M}_{\rm d,g,ss} = 2\dot{M}_{*,\rm ini}\left(\frac{1}{2} - \frac{r_{\rm p}}{\tilde{t}_{\rm ss}R_{\rm o}}\right)\tilde{t}_{\rm ss}^{-3/2}\exp\left(-\frac{r_{\rm p}}{\tilde{t}_{\rm ss}R_{\rm o}}\right),$$

Toy model

Gas accretion rate onto planets:

$$\dot{M}_{\rm p} = \min(\dot{M}_{\rm d,vis}, \dot{M}_{\rm p,geo})$$

$\dot{M}_{\rm d,vis}$ Accretion rate of the protoplanetary disk in radial direction by viscosity. In most cases, $\dot{M}_{\rm d,g,ss}$ is used.

$\dot{M}_{\rm p,geo}$ Accretion rate determined by the geometry of the gas accretion flow in the Hill sphere

$$\dot{M}_{\rm p,geo} = \dot{A}\Sigma_{\rm acc}$$

- $\Sigma_{\rm acc}$: Surface density of the feeding zone

Local gas depletion due to gap formation

(Duffell and MacFadyen 2013, Fung et al. 2014, Kanagawa et al. 2015)

Empirical formula by hydrodynamic simulations

$$\Sigma_{\rm acc} = \frac{1}{1+0.034K}\Sigma_{\rm ss}\exp\left(-\frac{t}{\tau_{\rm dep}}\right)$$

$$K = \left(\frac{M_p}{M_*}\right)^2\left(\frac{h_p}{r_p}\right)^{-5}\alpha^{-1}$$

- $\dot{A}$: Accretion rate of "Area" (Tanigawa and Watanabe 2002)

Empirical formula by hydrodynamic simulations

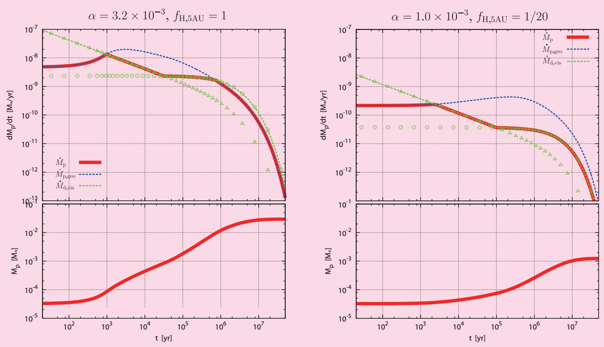
$$\dot{A} \simeq 0.29\left(\frac{h}{r_{\rm p}}\right)^{-2}\left(\frac{M_{\rm p}}{M_*}\right)^{4/3} r_{\rm p}^2\Omega_{\rm p},$$

Assumption

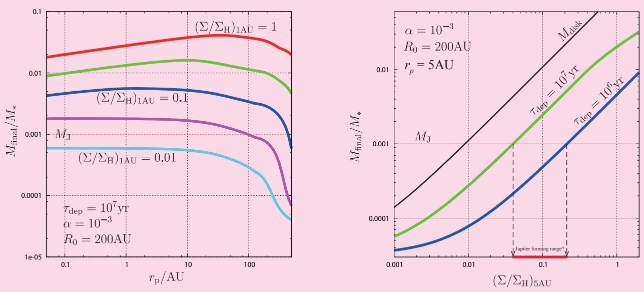
No photoevaporation and no planet migration

Results

Time evolution of planetary mass $\tau_{\rm dep} = 10^7{\rm yr}$, $R_{\rm o} = 200{\rm AU}$, $r_{\rm p} = 5{\rm AU}$

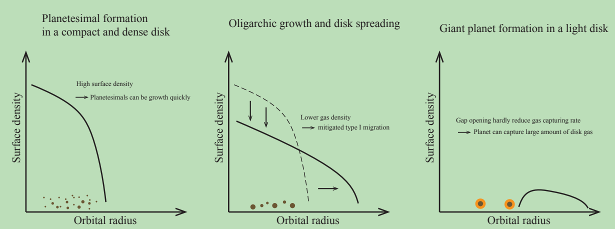


Final mass



Discussions

A possible path to produce Jupiter-size planets



Summary

We developed a new toy model to calculate gas accretion rate for long-term evolution by using new gap-opening formula.

→ Gap opening is hard to suppress growth of gaseous planets.
Disks with a MMSN mass produces planets with ~10 Jupiter masses.

Jupiter-mass planets requires a surface density as low as 1/20 of MMSN.

→ Infall of protoplanets due to type I migration can be avoided.
Our solar system?

Future works

Photo evaporation and type II migration