Possibility of giant planet formation by pebble accretion in Class 0/I phases

Yuki A. Tanaka [1]
[1] *Astronomical Institute, Tohoku University, 6-3 Aramaki, Aoba-ku, Sendai, Miyagi, 980-8578, Japan, 980-8578*
yuki.tanaka@astr.tohoku.ac.jp

Abstract

Several observations have revealed that axisymmetric sharp gaps in very young circumstellar disks, which may be indicative of the existence of giant planets at distant orbits. In addition, recent theoretical works suggest that the process called pebble accretion is important for planet formation in protoplanetary disks, because the process accelerates the growth of planetary cores. Here we investigate the possibility of giant planet formation via pebble accretion in much earlier phases, the gravitationally unstable disks of class 0/I young stellar objects. We find that under the conditions of the class 0/I disks, the pebble accretion timescales can be shorter compared to the typical protoplanetary disks due to larger gas and dust accretion rate, but also find that the accretion timescale is not always a decreasing function of the gas accretion rate. Then we calculate a required initial mass to form cores of gas giants within the lifetime of class 0/I phases by using estimated accretion timescales under several parameters, such as radial distances from the host star, gas accretion rates, and dust-to-gas mass ratio. In the most optimistic case, for example the dust-to-gas mass ratio is $f = 3f_{\rm solar}$, $\sim 10^{-4}M_\oplus$ objects at 10 au can grow to $10M_\oplus$ cores during the typical lifetime of the Class 0/I phases, 0.5 Myr. If this process works in the Class 0/I disks, it is expected that substructures of the disks caused by the planets can be observed by future radio observations, such as next generation very large array (ngVLA).

Key words: Planetary systems – planets and satellites: formation – planets and satellites: physical evolution – planet-disc interactions

1. Introduction

In the traditional planet formation models, it is assumed that kilometer-sized planetesimals are formed from dust particles in a protoplanetary disk, after which they grow up to become planetary embryos and/or protoplanets (e.g., **??**). This process is the so-called core accretion scenario. The formation processes of planetary systems are being actively studied both theoretically and observationally, but there still remain several issues to be resolved. For example, giant planet formation is thought to be difficult in the distant orbit in the gas-free condition, because the timescales to form planetary cores are too long (e.g., **?**).

Recently, an alternative model so-called pebble accretion has been proposed; small dust particles directly form large clumps via streaming instability (e.g., **?**), and the clumps grow fast by the accretion of migrating centimeter-sized pebbles that is enhanced by aerodynamic effects (e.g., **?**). In this process, the timescale of the growth of the cores of giant planets is shortened even in the distant region of the disks (**?**). Planet formation via pebble accretion in protoplanetary disks have been studied intensively, (e.g., **??**), but the possibility of pebble accretion in Class 0/I YSOs, the earlier phases of star and planet formation, has not been considered so far. It is shown that planetesimal formation from porous dust aggregate (**??**) is more preferable in the Class 0/I phase (**?**). This is one of our motivation to investigate the possibility of pebble accretion in Class 0/I phases.

Another important motivation of this work is the recent discoveries of disks with multiple rings and gaps, mainly achieved by the Atacama Large Millimeter/submillimeter Array (ALMA) (e.g., **?**). Many mechanisms have been proposed to reproduce the gap and ring structures, and one of possible gap-carving mechanism is embedded planets in the protoplanetary disks (e.g., **?**). Recent numerical works suggest that if gaseous planets exist in the disks, clear gaps and rings similar to those in several protoplanetary disks can be created due to disk-planet interaction (e.g., **??**).

However, the radii of the observed gaps are typically several tens of astronomical units (au), and whether planet formation at such large distances within the early phase of evolution of the protoplanetary disks is possible or not is still unclear. If earlier planet formation in the Class 0/I phases is possible, the observed gap structures around the Class I YSOs can be explained by the giant planet. Therefore, we investigate formation of solid cores of gaseous planets by pebble accretion in Class 0/I disks (**?**).

This article for the ngVLA memo series is based on our paper **?**, so if more detailed description or discussion are needed, please see the paper.

2. Models

2.1. Gas disk model

Here we assume one dimensional steady state structures for the gravitationally marginally unstable disk around the Class 0/I YSOs. Several theoretical works suggest that the gravitationally unstable disk frequently forms in Class 0/I YSOs (e.g., **?**). For the temperature profile of the disk, we assume that disk temperature T is determined by the stellar irradiation. In this case, radial temperature profile is given as follows based on **?** and **?**;

$$T = T_{\rm irr} \simeq 56 \left(\frac{r}{10\,{\rm au}}\right)^{-3/7} {\rm K}. \tag{1}$$

The aspect ratio of the gas disk $\hat{H}_{\rm gas}$ is written as follows:

$$\hat{H}_{\rm gas} \equiv \frac{H_{\rm gas}}{r} = \frac{c_{\rm s}}{r\Omega} \simeq 4.8\times 10^{-2} \left(\frac{M_*}{M_\odot}\right)^{-1/2} \left(\frac{r}{10\,{\rm au}}\right)^{2/7}, \tag{2}$$

where $H_{\rm gas}$, Ω, M_*, and $M_\odot$ are the pressure scale height of the gas disk, rotational frequency, stellar mass, and solar mass, respectively, and $c_{\rm s} = \sqrt{k_{\rm B}T/m_{\rm g}}$ is the sound speed, where $k_{\rm B}$ is the Boltzmann constant, and $m_{\rm g}$ ($\sim 3.9\times 10^{-24}$ g) is the mean molecular mass of the gas.

For the structures of the marginally gravitationally unstable gas disk, we use steady-state solution given by (**?**). We obtain

$$\Sigma_{\rm gas} \simeq 6.7\times 10^{2} \left(\frac{M_*}{M_\odot}\right)^{1/2} \left(\frac{r}{10\,{\rm au}}\right)^{-12/7} {\rm g\,cm^{-2}}, \tag{3}$$

$$\alpha \simeq 3.2\times 10^{-2} \left(\frac{\dot{M}_{\rm gas}}{10^{-6}\,M_\odot\,{\rm yr^{-1}}}\right) \left(\frac{r}{10\,{\rm au}}\right)^{9/14} \tag{4}$$

for gas surface density $\Sigma_{\rm gas}$, and α viscosity.

2.2. *Dust disk model*

For dust disk, we use the analytical model introduced by **?** in which radial migration of dust particle and dust growth are taken into account. In this model, radial dependence of dust size is written as

$$a_{\rm dust} \simeq 3.8\times 10^{2} \left(\frac{r}{10\,{\rm au}}\right)^{-47/28} \left(\frac{\dot{M}_{\rm gas}}{10^{-6}\,M_\odot\,{\rm yr^{-1}}}\right)^{1/2} \left(\frac{M_*}{M_\odot}\right) \left(\frac{\rho_{\rm int}}{0.1\,{\rm g\,cm^{-3}}}\right)^{-1} {\rm cm}, \tag{5}$$

and dust surface density is written as

$$\Sigma_{\rm dust} \simeq 1.0 \left(\frac{r}{10\,{\rm au}}\right)^{-31/28} \left(\frac{\dot{M}_{\rm gas}}{10^{-6}\,M_\odot\,{\rm yr^{-1}}}\right)^{1/2} {\rm g\,cm^{-2}}, \tag{6}$$

where $\dot{M}_{\rm gas}$, $\rho_{\rm int}$ are gas accretion rate, and internal density of the dust particle, respectively.

2.3. *Pebble accretion timescale*

For the derivation of the timescale of pebble accretion onto planetesimals and/or planetary embryos, we use the analytical model by **?**. Previous theoretical works have shown that the accretion mode of the pebbles are divided into two regimes, the 3D and 2D regimes (e.g., **?**). In addition, the accretion mode also can be divided into another two regimes, Bondi and Hill regimes, mainly depending on the mass of planetesimals/planetary embryos (**?**). In the general condition of the disk around Class 0/I YSOs, however, the accretion mode will be 3D and Bondi regime, with Epstein drag regime for dust particle (**?**). Therefore, the pebble accretion timescale can be written as

$$t_{\rm acc,3D} \simeq 9.4\times 10^{5} \kappa^{-2} \left(\frac{M_*}{M_\odot}\right)^{-3/4} \left(\frac{\dot{M}_{\rm dust}}{10^{-4} M_\oplus\,{\rm yr^{-1}}}\right)^{-1} \left(\frac{\dot{M}_{\rm gas}}{10^{-6}\,M_\odot\,{\rm yr^{-1}}}\right)^{1/4} \left(\frac{r}{10\,{\rm au}}\right)^{65/56} {\rm yr}, \tag{7}$$

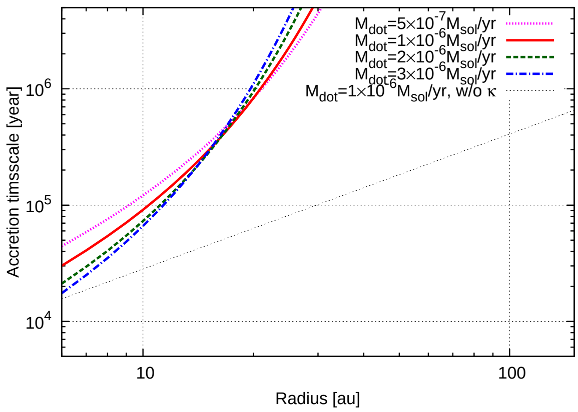

Fig. 1. Radial profiles of the accretion timescales with different gas accretion rates. We fixed $M_* = M_\odot$, $\dot{M}_{\rm dust} = f\dot{M}_{\rm gas}$, $f = 0.01$, and $M = 10^{-3} M_\oplus$ in this plot. The magenta dotted, red solid, green dashed, and blue dot-dashed lines correspond to the gas accretion rates $5\times 10^{-7}\,M_\odot\,{\rm yr}^{-1}$, $1\times 10^{-6}\,M_\odot\,{\rm yr}^{-1}$, $2\times 10^{-6}\,M_\odot\,{\rm yr}^{-1}$, and $3\times 10^{-6}\,M_\odot\,{\rm yr}^{-1}$, respectively. The black dotted line shows the accretion timescale when $\dot{M}_{\rm gas} = 10^{-6}\,M_\odot\,{\rm yr}^{-1}$ and $\kappa = 1$ are assumed, in order to show the importance of the reduction factor.

where $\dot{M}_{\rm dust}$ is dust accretion rate, and $M_\oplus$ is the mass of the Earth. In this equation, κ is the reduction factor introduced by **?**. This factor can be approximated to unity when Stokes number St is relatively small and the mass of a planetesimal is large (**?**). However, under the condition of typical Class 0/I YSOs, the reduction of accretion efficiency by the factor becomes important (**?**).

If we assume that the dust accretion rate is related to the gas accretion rate as $\dot{M}_{\rm dust} = f\dot{M}_{\rm gas}$, where f is the dust-to-gas mass ratio, and also assume $\dot{M}_{\rm gas} = 10^{-6} M_\odot\,{\rm yr}^{-1}$ and $f = 0.01$ as a fiducial model, we obtain the accretion timescale as follows;

$$t_{\rm acc,3D} \simeq 2.8\times 10^{4} \kappa^{-2} \left(\frac{M_*}{M_\odot}\right)^{-3/4} \left(\frac{r}{10\,{\rm au}}\right)^{65/56} {\rm yr}. \tag{8}$$

3. Results

3.1. *Accretion timescale*

As expressed by equation (**??**), the accretion timescale depends on the stellar mass, accretion rates of the gas and dust, radial distance, and dust-to-gas mass ratio. Here we assume that $M_* = M_\odot$, $\dot{M}_{\rm dust} = f\dot{M}_{\rm gas}$, and we fix the dust-to-gas mass ratio as $f = 0.01$. The accretion timescale also depends on the mass of the planetesimal M because the reduction factor κ is the function of M**?**. Here we assume that $M = 10^{-3} M_\oplus$.

Fig. **??** shows the radial dependence of the accretion timescale. We also show the accretion timescale when $\kappa = 1$ is assumed as a reference. If the reduction factor is neglected, the radial dependence of the accretion timescale is $t_{\rm acc} \propto r^{65/56}$, as described by equation (**??**), and therefore the timescale at $\sim$100 au is approximately ten times longer than that at $\sim$10 au. The black dotted line in Fig. **??** shows this relation. However, the effect of the reduction factor κ cannot be neglected for the condition of Class 0/I YSOs. This effect is shown in Fig. **??**; the accretion timescale described by the red solid line becomes larger than the black dotted line that κ is ignored. As shown in the figure, the accretion timescale increases rapidly in the distant region.

Fig. **??** shows that the accretion timescale decreases with the increase of the gas accretion rate in the region within ~ 20 au. The dependence of the accretion timescale on the dust accretion rate is $\propto \dot{M}_{\rm dust}^{-1}$ (equation (**??**)), and the dependence of the timescale on the gas accretion rate is $\propto \dot{M}_{\rm gas}^{1/4}$. Hence the resultant dependence of the timescale on the accretion rate becomes $\propto \dot{M}_{\rm gas}^{-3/4}$, when κ is neglected. In the distant region where $r \gtrsim 20$ au, however, the accretion timescale slightly increases with the gas accretion rate. This is caused by the dependence of St on the gas accretion rate. The larger gas accretion rate causes the larger St, and hence smaller reduction factor. Since the critical mass is large in the distant region, the effect of the reduction factor becomes significant.

3.2. *Growth of planets by the pebble accretion*

The definition of the accretion timescale is described as follows;

$$t_{\rm acc} \equiv \frac{M}{\dot{M}}. \tag{9}$$

We integrate equation (**??**) for the disk lifetime $t_{\rm life}$ to derive the required initial mass to form the core of the gas giants. If the core of the gas giant is formed via the pebble accretion in the class 0/I disk within its lifetime, it is a promising pathway to the early formation of the gas giants in distant orbits. In this calculation we set the final mass to 10 $M_\oplus$, because runaway gas accretion will occur when a planetary core becomes heavier than this value (e.g., **?**).

Figure **??** show the radial dependence of the required initial mass to form the 10 $M_\oplus$ core, with the difference gas accretion rate assuming $t_{\rm life} = 0.5$ Myr, $M_* = M_\odot$, $\dot{M}_{\rm dust} = f\dot{M}_{\rm gas}$, and $f = 0.01$, respectively. The figure indicates that when the gas accretion rate is $\dot{M}_{\rm gas} = 10^{-6}\,M_\odot\,{\rm yr}^{-1}$, the required initial mass is $\sim 5.0 \times 10^{-4}\,M_\oplus$ at 10 au. Therefore, if the embryo whose mass is $\sim 5.0 \times 10^{-4}\,M_\oplus$ forms at 10 au, it can grow to the core of the gas giant within the lifetime of the class 0/I phases. Since the accretion timescale is much longer in the distant region, the required initial mass have to be much larger.

The timescale of pebble accretion strongly depends on the gas accretion rate and the dust-to-gas mass ratio, therefore the required initial mass to form the core of the gas giant will also change significantly depending on these factors. Fig. (**??**) shows the radial dependence of the required initial mass to form the 10 $M_\oplus$ core, with the difference gas accretion rate assuming $t_{\rm life} = 0.5$ Myr, $M_* = M_\odot$, $\dot{M}_{\rm dust} = f\dot{M}_{\rm gas}$, and $f = 0.01$, respectively. Fig (**??**) also shows the dependence of the required initial mass, but the dust-to-gas mass ratio is set to larger value, $f = 3f_{\rm solar}$, and $f_{\rm solar} = 0.0149$ is the value for solar nebula (**?**). The blue dashed lines shows the contour for a required initial mass. From left to right, $10^{-4}M_\oplus$, $10^{-3}M_\oplus$, $10^{-2}M_\oplus$, and $10^{-1}M_\oplus$, respectively.

Because the pebble accretion timescale is proportional to

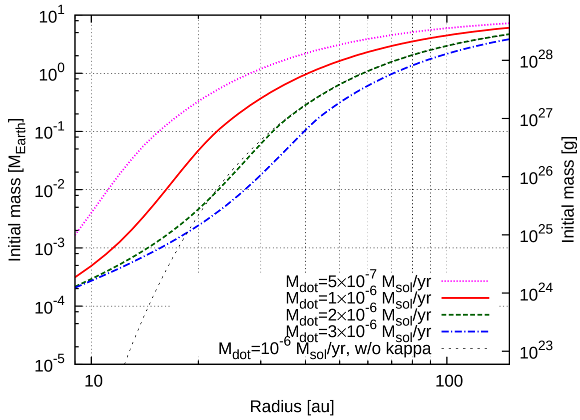

Fig. 2. Radial dependence of the required initial mass to form a 10 $M_\oplus$ core within the disk lifetime with different gas accretion rates. The horizontal axis is the radial distance from the central star in units of au. The vertical axes are the required initial mass, the left--hand side axis is in units of $M_\oplus$, and the right-hand side is in units of gram. $M_* = M_\odot$, $\dot{M}_{\rm dust} = f\dot{M}_{\rm gas}$, $t_{\rm life} = 0.5$ Myr, and $f = 0.01$ are assumed in this plot. The magenta dotted, red solid, green dashed, and blue dot-dashed lines correspond to the gas accretion rate, $5 \times 10^{-7}\,M_\odot\,{\rm yr}^{-1}$, $1 \times 10^{-6}\,M_\odot\,{\rm yr}^{-1}$, $2 \times 10^{-6}\,M_\odot\,{\rm yr}^{-1}$, and $3 \times 10^{-6}\,M_\odot\,{\rm yr}^{-1}$, respectively, and the blue dashed horizontal line shows $M = 10^{-7}\,M_\oplus$. The black dotted line shows the required initial mass when $1 \times 10^{-6}\,M_\odot\,{\rm yr}^{-1}$ and $\kappa = 1$ are assumed.

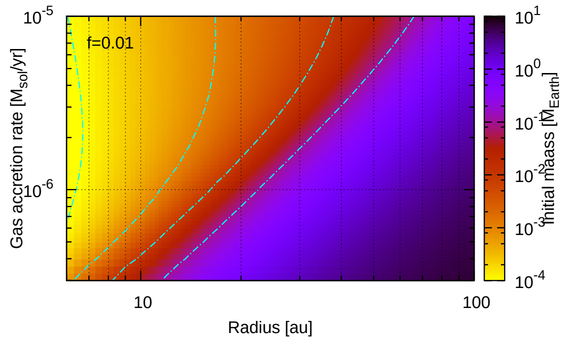

Fig. 3. Map of the required initial mass in a radius-gas accretion rate plane. The color bar corresponds to the required initial mass to form a 10 $M_\oplus$ core. $M_* = M_\odot$, $\dot{M}_{\rm dust} = f\dot{M}_{\rm gas}$, $t_{\rm life} = 0.5$ Myr, and $f = 0.01$ are assumed in this plot. The blue dashed lines shows the contour for a required initial mass. From left to right, $10^{-4}M_\oplus$, $10^{-3}M_\oplus$, $10^{-2}M_\oplus$, and $10^{-1}M_\oplus$, respectively.

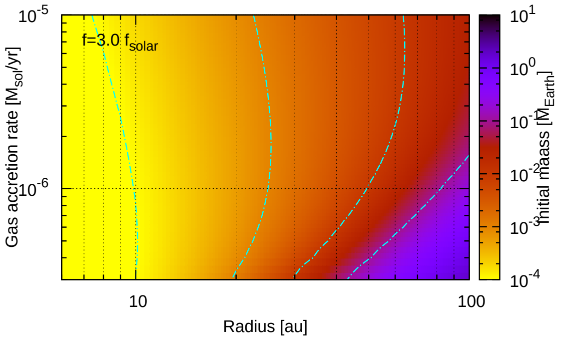

Fig. 4. Maps of the required initial mass in the radius-gas accretion rate plane. The color bars and axes are the same as in Figure **??**. $M_* = M_\odot$, $\dot{M}_{\rm dust} = f\dot{M}_{\rm gas}$, and $t_{\rm life} = 0.5$ Myr are assumed, and the dust-to-gas mass ratio is 3 $f_{\rm solar}$. The blue dashed lines shows the contour for a required initial mass same as in Fig. **??**.

$\dot{M}_{\rm dust}^{-1}$, the larger amount of dust lead to faster accretion. The larger dust-to-gas mass ratio leads to smaller required initial mass, due to the shorter accretion timescale. For dust rich condition, as shown in Fig (**??**), a larger dust component strongly enhances the accretion rate of the pebbles and reduces the required initial mass. In the case of $f = 3f_{\rm solar}$, a $\sim 10^{-3} M_\oplus$ embryo at $\gtrsim 20$ au can grow to a 10 $M_\oplus$ core. This results suggest that if the planetary embryo whose mass is $\sim 10^{-3} M_\oplus$ is formed, it can grow to the core of the gas giant, and thus the giant planet can form during the Class 0/I phases.

4. Future prospects for ngVLA

We showed that the required initial mass to form the 10 $M_\oplus$ core that can grow into the gas giant at 10 au is $\sim 5.0 \times 10^{-4}$ $M_\oplus$ when we assume the gas accretion rate is $\sim 10^{-6}$ $M_\odot\,{\rm yr}^{-1}$, the dust-to-gas mass ratio is 0.01, and the disk lifetime is 0.5 Myr. In addition, for the most optimistic case, for example, the formation of the core of the giant planet is possible at $\sim$ 10 au from the host star when $\dot{M}_{\rm gas} \sim 3.0 \times 10^{-7} - 10^{-6}\, M_\odot\,{\rm yr}^{-1}$ and $f = 3f_{\rm solar}$, and the embryo mass is comparable to Ceres's mass, $\sim 10^{-4} M_\oplus$.

It is unclear that such large objects can form in the disk round Class 0/I YSOs, so both theoretical and observational works will be needed. As described by equation (**??**), the size of the dust grain can be a few centimeter or larger in Class 0/I phases (**??**). The dust grain of this size is difficult to observe by current radio telescopes such as ALMA. However, future facilities that using longer wavelengths such as ngVLA, cm-sized dust grain in Class 0/I YSOs will be detectable. Therefore, it is expected that dust evolution process in younger stage of star and planet formation will be observable, and the possibility of the planet formation and growth via pebble accretion in Class 0/I YSOs will be testable. In addition, if a gaseous planet already formed in Class 0/I YSOs, the disk-planet interaction will generate substructures in the disk similar to that observed in many protoplanetary disks. These substructures will also be observable by future radio telescopes, and future observations of such substructures will benefit our understanding of the star and planet formation processes.

References

ALMA Partnership., et al. 2015, ApJL, 808, L3
Chiang, E. I. & Goldreich, P., 1997, ApJ, 490, 368
Dipierro, G., Price, D., Laibe, G., et al. 2015, MNRAS, 453, L73
Dodson-Robinson, S. E. and Veras, D. and Ford, E. B., et al. 2009, ApJ, 707, 79
Goldreich, P. & Tremaine, S., 1980, ApJ, 241, 425
Guillot, T., Ida, S. & Ormel, C. W., 2014, A&A, 572, A72
Hayashi, C. and Nakazawa, K. & Nakagawa, Y., 1985, Protostars and Planets II, 1100
Ida, S. and Guillot, T. and Morbidelli, A., 2016, A&A, 591, A72
Kanagawa, K. D., Muto, T., Tanaka, H., et al. 2015, ApJL, 806, L15
Kataoka, A., Tanaka, H., Okuzumi, S., et al. 2013, A&A, 557, L4
Kusaka, T., Nakano, T. & Hayashi, 1970, Progress of Theoretical Physics, 44, 1580
Lambrechts, M. & Johansen, A., 2012, A&A, 544, A32
Lodders, K. 2003, ApJ, 591, 1220
Mizuno, H. 1980, Progress of Theoretical Physics, 64, 544
Nakamoto, T. & Nakagawa, Y., ApJ, 1994, 421, 640
Okuzumi, S., Tanaka, H., Kobayashi, H., et al. 2012, ApJ, 752, 106
Ormel, C. W. & Klahr, H. H., 2010, A&A, 520, A43
Ormel, C. W. & Kobayashi, H., 2012, ApJ, 747, 115
Safronov, V. S. 1972, Evolution of the protoplanetary cloud and formation of the earth and planets.
Tanaka, Y. A. & Tsukamoto, Y. MNRAS, 484, 1574
Tsukamoto, Y., Okuzumi, S. & Kataoka, A. 2017, ApJ, 838, 151
Youdin, A. N. & Goodman, J., 2005, ApJ, 620, 459