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A possible scenario of the formation of our solar system in a gas depleted disk

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Abstract

First, we study the final masses of giant planets growing in protoplanetary disks through capture of disk gas, by employing empirical formulae for the gas capture rate and a shallow disk gap model, which are both based on hydrodynamic simulations. We find that, for planets less massive than 10 Jupiter masses, their growth rates are mainly controlled by the gas supply through the global disk accretion, and the gap opening does not limit the accretion. The insufficient gas supply compared with the rapid gas capture causes a depletion of the gas surface density even at the outside the gap, which can create an inner hole in the disk. Second, our findings are applied to the formation of our solar system. For the formation of Jupiter, a very low-mass gas disk of several Jupiter masses is required at the beginning of its gas capture because of the continual capture. Such a low-mass gas disk with sufficient solid material can be formed through viscous evolution from a compact disk of initial size ~10 au. By viscous evolution with a moderate viscosity of $\alpha \sim 10^{-3}$, most of the disk gas accretes onto the Sun and a widely spread low-mass gas disk remains when the solid core of Jupiter starts gas capture at $\sim 10^{-7}$ yr. A very low-mass gas disk also provides a plausible path where type I and II planetary migrations are both suppressed significantly. In particular, the type II migration of Jupiter-size planets becomes inefficient because of the additional gas depletion due to the rapid gas capture by such planets.

1. Introduction

Giant planets like Jupiter and Saturn are thought to be formed in a gas disk by capturing the disk gas [4][5]. The gas-accretion growth of a giant planet is expected to be terminated when the planet's own strong gravity creates a gap. Two well-known gap-opening conditions have been widely used: the thermal condition and the viscous condition [2]. After a while, an analytic formula for the gap profile was suggested [6], which gives shallower gap than the traditional conditions. However, recent hydrodynamic simulations have shown that the gap is much shallower than the traditional prediction, and even shallower than the analytic estimate. This means that the formation of gap would be more difficult than previously thought, and thus this forces us to reconsider the mechanism to terminate the growth of the giant planets.

In this study, we construct a toy model to describe the giant planet growth by capturing protoplanetary gas disks, and examine the final masses of the giant planets. We then apply the model to our solar system, and suggest a possible scenario of the formation of our solar system by considering the shallower gap model.

2. Methods

We consider a globally evolving protoplanetary disk with the self-similar solution. In the disk, a proto-giant planet starts to capture the disk gas with a rate given by our model. The formula of the gas accretion rate onto the planet is given by the combination of the three terms:

$$\dot{M}_p = \min(\dot{M}_{p,hydro}, \max(\dot{M}_{d.global}, \dot{M}_{d,local})),$$

where $\dot{M}_{p,hydro}$ is the gas accretion rate onto the planet by hydrodynamic gas flow, $\dot{M}_{d,global}$ is the steady-state radial accretion rate in the global viscous disk, and $\dot{M}_{d,local}$ is the transient viscous disk accretion rate just after the planet starts the gas capturing growth. The term $\dot{M}_{p,hydro}$ considers the hydrodynamic gas accretion onto the planet [7], and the gap deepening [1], both of which are based on the numerical simulations. The three terms are given in explicit functions of disk mass, disk scaleheight, viscous coefficient, disk initial size, planet mass and orbital radius, and time after the onset of the gas capture. Once we obtain the formula of the accretion rate explicitly, we can integrate the formula with respect to time, which gives us the evolution and history of the giant planet growth.

3. Results

We performed a parameter study systematically, and found that, for planets less than 10 Jupiter masses, their growth rates are mainly controlled by the gas supply through the global disk accretion. This means that the gap is no effect to reduce the gas accretion rate onto the planets until they reach 10 Jupiter masses.

4. Possible scenario of the formation of our solar system

If the gap is little effect to reduce or terminate the growth rate, the final mass would be much larger than the current Jupiter mass if we consider the "standard" disk model. Thus a very low-mass gas disk is required when the proto-giant planet starts the dynamical gas capture. But at the same time, enough solid mass is required to produce the solid cores that can trigger the dynamical gas accretion. To solve the difficulty, we here propose that the initial protoplanetary disk is a very compact (~10AU) with about 18 Jupiter masses with the solar composition. In the dense disk, dust growth is very fast to be planetesimals, and quickly decoupled from the disk gas. The following disk viscous accretion onto the star reduces disk gas only, not for the planetesimals, which realize the low-mass gas disk with high metallicity. When the gas disk is reduced to be around 4 Jupiter masses, the solid core reaches the critical mass (~10 Earth masses) and starts the gas capture. This scenario is also preferable in terms of type I and II migrations. If solid protoplanets grows in the gas-depleted disk, type I migration rate is reduced and the longstanding problem of falling solid planets is mitigated to considerable degree. In addition, our model consider the local depletion of disk gas near the planet orbit in steady state [3], which even reduces torque from the disk onto the planet. Figure 1 shows the growth-migration curves of the protoplanets in the gas capturing phase. Our model reproduces the population of the extrasolar system, which is very difficult by the previous prediction.

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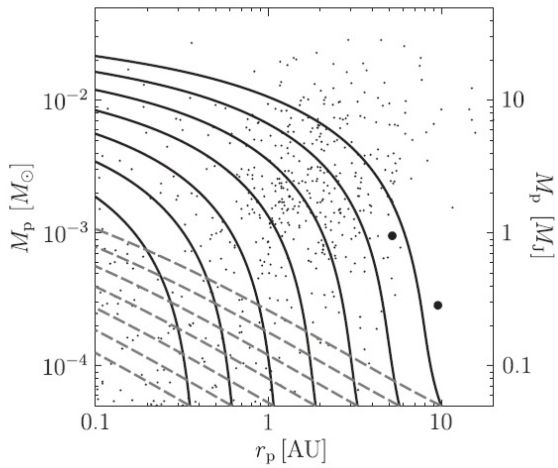

Figure 1. Growth-migration curves. Solid curves show evolution paths based on our result, and dashed curves are the cases where the traditional type II migration is used. Small dots show the distribution of extrasolar planets. Filled circles are Jupiter and Saturn.

References

[1] Duffell, P, and MacFadyen: Gap opening by extremely low-mass planets in a viscous disk, The Astrophysical Journal, 749, 41, 2013.

[2] Lin, D. N. C., and Papaloizou, J. C. B.: On the tidal interaction between protostellar disks and companions, Protostars and Planets III, 749, 1993.

[3] Lubow, S. H., and D'Angelo, G.: Gas flow across gaps in protoplanetary disks, The Astrophysical Journal, 641, 526. 2006

[4] Mizuno, H.: Formation of giant planets, Progress of Theoretical Physics, 64, 544, 1980.

[5] Pollack, J. B., Hubickyj, O., Bodenheimer, P., Lissauer, J. J., Podolak, M., and Greenzweig, Y.: Formation of Giant Planets by Concurrent Accretion of Solids and Gas, Icarus, 124, 62, 1996.

[6] Tanigawa, T. and Ikoma, M.: A systematic study of the final masses of gas giant planets, The Astrophysical Journal, 667, 557, 2007.

[7] Tanigawa, T. and Watanabe, S.: Gas accretion flows onto giant protoplanets: high-resolution two-dimensional simulations, The Astrophysical Journal, 580, 506, 2002.