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Necessary conditions for the formation of gas giant planets

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Abstract

Massive planetary cores ($\sim$ 10 Earth masses) trigger rapid gas accretion to form gas giant planets such as Jupiter and Saturn. We investigate the core growth and the possibilities for cores to reach such a critical core mass. At the late stage, planetary cores grow through collisions with small planetesimals. Collisional fragmentation of planetesimals, which is induced by gravitational interaction with planetary cores, reduces the amount of planetesimals surrounding them, and thus the final core masses. Starting from small planetesimals that the fragmentation rapidly removes, less massive cores are formed. However, planetary cores acquire atmospheres that enlarge their collisional cross section before rapid gas accretion. Once planetary cores exceed about Mars mass, atmospheres significantly accelerate the growth of cores. We show that, taking into account the effects of fragmentation and atmosphere, initially large planetesimals enable formation of sufficiently massive cores. On the other hand, because the growth of cores is slow for large planetesimals, a massive disk is necessary for cores to grow enough within a disk lifetime. If the disk with 100 km-sized initial planetesimals is 10 times as massive as the minimum mass solar nebula, planetary cores can exceed 10 Earth masses in the Jovian planet region (> 5 AU).

1. Introduction

Gas giant planets form in gaseous disks. In the core-accretion model, the accretion of planetesimals produces cores of giant planets. Once a core has reached a critical mass $\sim$ 10 Earth masses, it can rapidly accrete gas to form a gas giant planet [1]. Gas giants must form within the lifetime of gaseous disks ($\lesssim 10$ Myr).

2. Results

The runaway growth of km-sized or larger planetesimals produces a single large body, a planetary embryo, in each region of a disk. As long as the embryos have accreted all surrounding planetesimals within their feeding zones, embryo masses finally reach the isolation mass. However, as embryos grow, they dynamically excite surrounding planetesimals, which induces collisional fragmentation. The planetesimals are ground down by successive collisions. The very small resulting bodies rapidly drift inward due to strong gas drag. Since the planetesimals are depleted by the fragmentation, embryo growth stalls far short of the isolation mass. We analytically derive final embryo masses, $M_{\rm a}$ and $M_{\rm na}$, with and without atmosphere, respectively. The solution indicates that final embryo masses are as small as Mars mass in the minimum-mass solar nebula model (MMSN [2]) and that an $\sim 10\times$MMSN disk is needed to form giant planets. Fig. 1 shows $M_{\rm a}$ and $M_{\rm na}$ for 10×MMSN. Since high relative velocities are needed to collisionally break large planetesimals due to their strong self-gravity, the collisional depletion of such planetesimals takes longer. Embryos can thus be massive for large initial planetesimals. If we neglect the atmosphere, final embryos cannot exceed $10 M_\oplus$ as long as $r_0 < 100$ km. If the atmosphere is included, the final mass does not drastically increase around 5-10 AU, where gas giant planets were likely to have formed in the solar system. Therefore, at least 100 km-sized initial planetesimals are needed to form gas giants in this region.

We then perform simulations, where a disk is divided into 8 concentric annuli in 3–35 AU and each annulus contains a set of mass batches. We set the mass ratio of a batch to its smaller adjacent batch to be 1.2, which can reproduce the collisional growth of bodies resulting from N-body simulation without fragmentation [3] and the analytical solution of mass depletion due to collisional grinding [4]. The mass and velocity evolution of bodies and their radial transport are calculated. The simulation incorporates collisional enhancement due to the atmosphere provided by the previous study [5].

The simulations for embryo formation starts from a monodisperse mass population of planetesimals of mass m_0 and radius r_0 with material density $1\,\mathrm{g\,cm^{-3}}$ around a central star of the solar mass $M_\odot$. Their initial eccentricities e and inclinations i are set to $e = 2i = (2m_0/M_\odot)^{1/3}$. For 10×MMSN, results for these simulations are summarised in Fig. 1, where the embryo masses after 10^7 years are compared to analytical formulae for final embryo masses. Embryo growth stall around M_a inside 5 AU ($r_0 = 100\,\mathrm{km}$), 20 AU ($r_0 = 10\,\mathrm{km}$), and 30 AU ($r_0 = 1\,\mathrm{km}$), although embryos are smaller than M_a in the outer disk because of their slow growth. However, embryos exceed M_a inside 5 AU for $r_0 = 10\,\mathrm{km}$. This excess comes from the embryo growth through collisional accretion with bodies drifting from outside, which effect we did not consider in the analysis. However, such further growth cannot help the core formation around 5–10 AU. Therefore, we conclude that embryos can exceed the critical core mass in the formation region of Jupiter and Saturn if initial planetesimals are as large as 100km in an massive disk (10×MMSN).

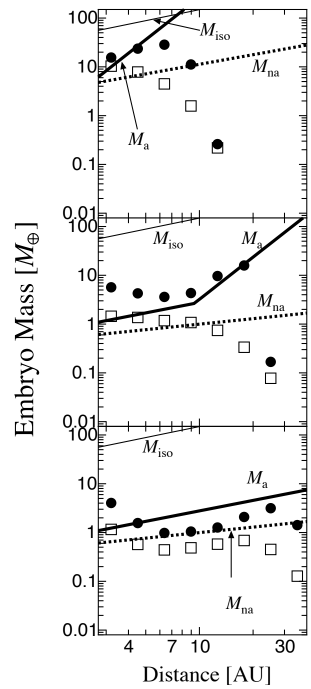

Figure 1: Embryo masses with (circles) and without (squares) atmosphere after 10^7 years for a 10×MMSN disk as a function of distance form the central star. We set $m_0 = 4.2 \times 10^{21}\,\mathrm{g}$ ($r_0 = 100\,\mathrm{km}$) (top), $m_0 = 4.2 \times 10^{21}\,\mathrm{g}$ ($r_0 = 10\,\mathrm{km}$) (middle), and $m_0 = 4.2 \times 10^{15}\,\mathrm{g}$ ($r_0 = 1\,\mathrm{km}$), (bottom). Solid lines indicate M_a, the analytical solution for a final mass of embryo with atmosphere. Dotted lines represent M_na, the final embryo mass analytically driven in the case without atmosphere. Thin lines show the isolation mass, M_iso.

3. Summary and Conclusions

If the atmosphere is not taken into account, collisional fragmentation suppresses planetary embryo growth substantially. As a result, embryos cannot reach the critical core mass of $\sim 10 M_\oplus$ needed to trigger rapid gas accretion to form gas giants. The final masses are about Mars mass in a MMSN disk [3]. Embryo's atmosphere accelerates the embryo growth and may increase the final embryo mass by up to a factor of ten. We have derived the final mass, M_a, analytically. These final masses are in good agreement with the results of statistical simulations.

The embryo growth depends on the disk mass and initial planetesimal sizes. We have performed statistical simulations to calculate the final embryo masses over a broad range of parameters. We took 1–10×MMSN and initial planetesimal radius $r_0 = 1$–$1000\,\mathrm{km}$. We found that planetary embryos can exceed $10 M_\oplus$ within 8-9 AU for 10×MMSN and $r_0 = 100\,\mathrm{km}$. Other sets of parameters cannot produce massive cores at 5–10 AU. For example, embryo's mass can exceed $10\,M_\oplus$ for $r_0 = 10\,\mathrm{km}$ around 20 AU. Therefore, we conclude that a massive disk ($\sim$ 10×MMSN) with $r_0 \sim 100\,\mathrm{km}$ and $f \lesssim 0.01$ is necessary to form gas giant planets around 5–10 AU. This condition for large embryo formation is independent of the material strength and/or structure of bodies, because the strength of 100km-sized or larger bodies is largely determined by their self-gravity.

References

[1] Mizuno, H., Nakazawa, K., Hayashi, C.: Dissolution of the primordial rare gases into the molten earth's material., Earth and Planetary Science Letters Vol. 50, p.p. 202-210, 1980.

[2] Hayashi, C.: Structure of the Solar Nebula, Growth and Decay of Magnetic Fields and Effects of Magnetic and Turbulent Viscosities on the Nebula. Progress of Theoretical Physics Supplement, Vol. 70, pp. 35-53, 1981.

[3] Kobayashi, H., Tanaka, H., Krivov, A. V., and Inaba, S.: Planetary growth with collisional fragmentation and gas drag, Icarus, Vol. 209, pp. 836-847 2010.

[4] Kobayashi, H. and Tanaka, H.: Fragmentation model dependence of collision cascades, Icarus, Vol. 206, pp. 735-746, 2010.

[5] Inaba, S., Ikoma, M.: Enhanced collisional growth of a protoplanet that has an atmosphere, Astronomy and Astrophysics, Vol. 410, pp. 711-723, 2003.