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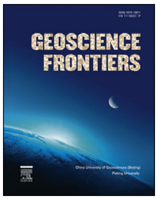

Research paper

The origin of high eccentricity planets: The dispersed planet formation regime for weakly magnetized disks

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A R T I C L E I N F O

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In the tandem planet formation regime, planets form at two distinct sites where solid particles are densely accumulated due to the on/off state of the magnetorotational instability (MRI). We found that tandem planet formation can reproduce the solid component distribution of the Solar System and tends to produce a smaller number of large planets through continuous pebble flow into the planet formation sites. In the present paper, we investigate the dependence of tandem planet formation on the vertical magnetic field of the protoplanetary disk. We calculated two cases of $B_z = 3.4 \times 10^{-3}$ G and $B_z = 3.4 \times 10^{-5}$ G at 100 AU as well as the canonical case of $B_z = 3.4 \times 10^{-4}$ G. We found that tandem planet formation holds up well in the case of the strong magnetic field ($B_z = 3.4 \times 10^{-3}$ G). On the other hand, in the case of a weak magnetic field ($B_z = 3.4 \times 10^{-5}$ G) at 100 AU, a new regime of planetary growth is realized: the planets grow independently at different places in the dispersed area of the MRI-suppressed region of $r = 8–30$ AU at a lower accretion rate of $\dot{M} < 10^{-7.4} M_\odot \text{ yr}^{-1}$. We call this the "dispersed planet formation" regime. This may lead to a system with a larger number of smaller planets that gain high eccentricity through mutual collisions.

1. Introduction

A star is born together with the planets orbiting around it from the gravitational collapse of a dense core of a molecular cloud (e.g., Bouvier et al., 2007). This collapse produces a centrifugally supported thin disk around the protostar, and the solid particles grow from the submicron scale to the order of 10^4 km in the disk. Recent observations have shown that planets can be found around stars universally, and the number of confirmed exoplanets is 2107 as of April 2016 (http://exoplanet.eu/catalog/). Many of the exoplanets, however, do not resemble the planets in our Solar System. For example, some exoplanets have large orbital eccentricities and are called eccentric planets (Marcy and Butler, 1996).

Theoretically, planet formation has also been investigated by many researchers since the early 1970s, and the core accretion model has been proposed as a formation scenario for planets. In the classical core accretion model, planetesimals form first; these are solid bodies on the order of 10 km. They are produced by the gravitational instability of the particle layer (e.g., Safronov, 1969; Goldreich and Ward, 1973; Hayashi et al., 1985) or the mutual sticking of particles (Weidenschilling, 1977a; Weidenschilling and Cuzzi, 1993). After planetesimals form, they coagulate with each other, which leads to runaway growth (Wetherill and Stewart, 1989) and then oligarchic growth (Kokubo and Ida, 1998) until they reach the isolation masses to form the planetary core. If this core reaches the critical core mass (i.e., several Earth masses) before the gas depletion of the protoplanetary disk, it rapidly attracts the surrounding gas and becomes a gas or icy giant (e.g., Mizuno, 1980; Pollack et al., 1996). Otherwise, it remains a terrestrial planet.

The classical core accretion model had three difficulties: the formation timescale problem, dust fragmentation and infall problem, and planet migration problem. Nevertheless, recent investigations have gradually solved these difficulties. First, the formation timescale problem was overcome by pebble accretion (Johansen et al., 2006, 2007; Johansen and Youdin, 2007; Johansen et al., 2009, 2011; Johansen and Lacerda, 2010; Ormel and Klahr, 2010; Lambrechts and Johansen, 2012, 2014). The particle growth by pebble capturing accelerates the planetary growth. Second, the dust fragmentation and infall problem was eluded by the introduction of the porous nature of icy particles beyond the snowline. Although meter-sized compact particles are selectively lost from the disk by radial infall (~1000 yrs), the particles can quickly grow

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as large as the mean free path of the gas molecule if the porous aggregation is considered in the icy region ($T_m < 150$ K). This changes the gas drag law on the particles from the Epstein regime to the Stokes regime, which eventually terminates the radial drift of a particle when its mass reaches $\sim 10^{10}$ g (Okuzumi et al., 2012). Therefore, the dust infall problem in the classical model has been partially overcome, although the problem still remains in the rocky region ($T_m > 150$ K). Furthermore, the reduction of the relative particle–particle velocity also mitigates the fragmentation problem. Third, the planet migration problem was solved by introducing the dynamic term of the corotation torque. The gravitational interaction between the planet and gas disk causes planetary migration over a short timescale, but introducing the dynamic term in the torque formula reduces the inward migration rate considerably (Paardekooper, 2014; Sasaki and Ebisuzaki, 2016).

Motivated by the recent progress in planet formation theory, we (Ebisuzaki and Imaeda, 2016, hereafter paper I) constructed a steady-state one-dimensional model of the accretion disk around a protostar based on the α-model of an accretion disk according to the standard formulation of Shakura and Sunyaev (1973) and Lynden-Bell and Pringle (1974). We further investigated the particle evolution within this disk. In order to construct the disk model, we considered the magnetorotational instability (MRI) (Balbus and Hawley, 1991; Hawley and Balbus, 1991), layered accretion (Gammie, 1996), and ionization due to the galactic cosmic rays and radioactive nuclei (Umebayashi and Nakano, 1988). The ionization due to thermal collision (Balbus and Hawley, 2000) was also considered as the ionization source. For the particle evolution, we considered porous aggregation and compaction (Okuzumi et al., 2012; Kataoka et al., 2013).

We found that the disk is divided into three regions by two distinct locations: the outer MRI front at r_{out} and the inner MRI front at r_{in}; these locate around $7\,\mathrm{AU} \le r_{\mathrm{out}} \le 60$ AU and $0.2\,\mathrm{AU} \le r_{\mathrm{in}} \le 1$ AU, respectively (see Fig. 1a). First, outside the outer MRI front, MRI takes place, and the disk is turbulent because of the ionization due to the galactic cosmic rays (Umebayashi and Nakano, 1988). Second, between the two MRI fronts, no MRI occurs around the midplane (MRI-suppressed region) (e.g., Sano and Miyama, 1999; Sano et al., 2000). This turbulent-free area is sandwiched by two turbulent surface layers (i.e., turbulent envelopes), where the ionization degree is high enough to activate MRI (Gammie, 1996). Third, inside the inner MRI front (inner turbulent region: ITR), MRI takes place due to the thermal ionization of K and Na (Balbus and Hawley, 2000). This corresponds to the location where the disk temperature is $T_m = 1000$–1300 K. Finally, the disk is truncated by the stellar magnetic field at the Alfvén radius ($0.01\,\mathrm{AU} \le r_A \le 0.04$ AU). This three-region structure is consistent with the recent comprehensive review by Armitage (2011).

We further investigated the particle drift and sedimentation to the midplane in the disk (Nakagawa et al., 1986). In contrast to the classical core accretion model, we considered both the particle growth by mutual sticking with porosity evolution (Okuzumi et al., 2012; Kataoka et al., 2013) and the gravitational instability of the particle sub-disk (Yamoto and Sekiya, 2004). As a result, the gravitational instability takes place after the particles are completely decoupled from the turbulent gas. This is different from the classical view, where the gravitational instability takes place during the partial decoupling stage, and may be significant to avoiding the dust infall problem. Such a late-stage gravitational instability was reported by Carballido et al. (2006) to explain the formation of the Kuiper belt objects.

In paper I, we showed that planet formation is restricted to two distinct sites in the disk: around the outer MRI front and the inner MRI front. At the outer MRI front, porous icy aggregates grow (Okuzumi et al., 2012; Kataoka et al., 2013) and are subjected to the gravitational instability of the particle sub-disk to make the planetesimals (Yamoto and Sekiya, 2004). Then, they finally reach $10^{27}\mathrm{g} \sim M_\oplus$ within a million years to become icy planets or gas giant cores. On the other hand, volatile-free rocky planetesimals form around the inner MRI front because the distraction associated

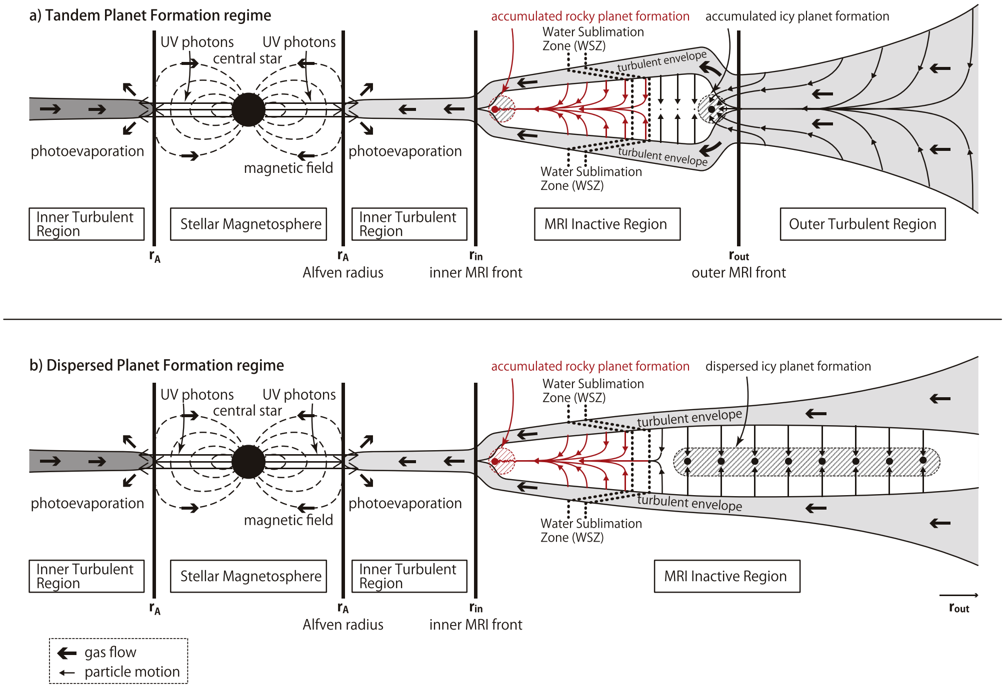

Figure 1. Schematic cross-section of the two regimes of planet formation. (a) Tandem planet formation regime: Planet formation is strictly restricted around two sites: the outer and inner MRI fronts. Continuous pebble supplied by the particle drift to the sites sustains the rapid growth of planets at these locations. (b) Dispersed planet formation: Icy planet formation is dispersed to the entire region of the disk outside the snowline (WSZ), although the same rocky planet formation takes place at the inner MRI front.

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