Geoscience Frontiers xxx (2016) 1–9

HOSTED BY

ELSEVIER

Contents lists available at ScienceDirect

China University of Geosciences (Beijing)

Geoscience Frontiers

journal homepage: www.elsevier.com/locate/gsf

Research paper

Tandem planet formation for solar system-like planetary systems

Yusuke Imaeda*, Toshikazu Ebisuzaki

RIKEN, 2-1, Hirosawa, 351-0198, Japan

A R T I C L E I N F O

Article history:
Received 18 March 2016
Received in revised form
13 June 2016
Accepted 17 June 2016
Available online xxx

Keywords:
Accretion disk
Planet formation
Magneto-rotational instability
Origin of life

A B S T R A C T

We present a new united theory of planet formation, which includes magneto-rotational instability (MRI) and porous aggregation of solid particles in a consistent way. We show that the "tandem planet formation" regime is likely to result in solar system-like planetary systems. In the tandem planet formation regime, planetesimals form at two distinct sites: the outer and inner edges of the MRI suppressed region. The former is likely to be the source of the outer gas giants, and the latter is the source for the inner volatile-free rocky planets. Our study spans disks with a various range of accretion rates, and we find that tandem planet formation can occur for $\dot{M} = 10^{-7.3} - 10^{-6.9} M_{\odot}$ y r^{-1}. The rocky planets form between 0.4–2 AU, while the icy planets form between 6–30 AU; no planets form in 2–6 AU region for any accretion rate. This is consistent with the gap in the solid component distribution in the solar system, which has only a relatively small Mars and a very small amount of material in the main asteroid belt from 2–6 AU. The tandem regime is consistent with the idea that the Earth was initially formed as a completely volatile-free planet. Water and other volatile elements came later through the accretion of icy material by occasional inward scattering from the outer regions. Reactions between reductive minerals, such as schreibersite (Fe_3P), and water are essential to supply energy and nutrients for primitive life on Earth.

1. Introduction

The process of planet formation involves growing 1000–10,000 km-sized objects from micron-sized dust grains in the gaseous disk around a newly born star; this disk is formed by the gravitational collapse of a slightly rotating dense molecular cloud (e.g. Bouvier et al., 2007). Planet formation has been vigorously investigated by many researchers (e.g. Safronov, 1969; Goldreich and Ward, 1973; Weidenschilling, 1977a; Hayashi et al., 1985; Wetherill and Stewart, 1989) and the core accretion scenario has been generally accepted as the standard model of planet formation. It can be divided into the following steps. First, submicron-sized interstellar dust grains grow into cm-sized pebbles through mutual collisions and gradually settle to the midplane of the disk to form a sub-disk of pebbles (e.g. Weidenschilling, 1977a; Nakagawa et al., 1981; Weidenschilling and Cuzzi, 1993). Second, the pebbles grow into km-sized planetesimals via gravitational instability (e.g. Safronov, 1969; Hayashi, 1972, 1981; Goldreich and Ward, 1973; Hayashi et al., 1985). Third, the gravity of planetesimals causes runaway growth (e.g. Wetherill and Stewart, 1989), and later oligarchic growth, that results in Mars-sized protoplanets (e.g. Kokubo and Ida, 1998). Finally, the protoplanets grow further by pebble accretion (Johansen et al., 2006) and occasional giant impacts (Kokubo and Ida, 2012). The protoplanets can become gas giants if they reach the critical core mass for trapping gas ($\sim$3–10 $M_{\oplus}$, where $M_{\oplus}$ is the Earth mass) before the gas disk dissipates (Mizuno, 1980; Pollack et al., 1996); otherwise they remain terrestrial planets (Chambers and Wetherill, 1998) without gas envelopes (atmospheres).

There are three major difficulties in forming the solar system this way. First, Weidenschilling (1977b) estimated the solid component distribution in the present solar system and found a gap between 2 and 5 AU, which is difficult to explain using the standard model. Second, the eccentricities of the planets in the solar system are small (0.01–0.1). Kokubo and Ida (1998) estimated that the final mass of protoplanets at 1 AU is of the order of a Mars mass (which is about 10 times less massive than Earth). This indicates that $\sim$10 Mars-sized objects were distributed in the Earth forming region at the late oligarchic growth stage and that subsequent giant impacts are inevitable for forming the present Earth.

* Corresponding author.
E-mail address: yusuke.imaeda@riken.jp (Y. Imaeda).
Peer-review under responsibility of China University of Geosciences (Beijing).

http://dx.doi.org/10.1016/j.gsf.2016.06.011

Naive consideration gives that the final eccentricities of the planets in such system become significantly large, but this is inconsistent with the present orbit of the Earth. Therefore, given the constraints from planet eccentricities, evolution without giant impacts might be preferable for solar system formation models. Although post giant impact eccentricities may damp due to dynamical friction with the remaining gas disk (Kominami and Ida, 2002) or with residual planetesimals (O'Brien et al., 2006), both are likely to disappear well before the last stage of planet formation.

Finally, the amount of H_2O in the Earth is also difficult to explain. The present oceans mass of the Earth, M_{oce}, is estimated to be 0.023 wt.% of $M_{\oplus}$. Studies of water and trace elements in the mid-ocean ridge indicate that the upper mantle contains 50–200 ppm water (Michael, 1988; Dixon et al., 2002; Hirschmann, 2006; Maruyama and Okamoto, 2007). This upper mantle water is likely to have been transferred from the surface by plate subduction. From the pre-Cambrian period to the present, the sea level decreased by about 600 m, which corresponds to 0.2 M_{oce}. Maruyama and Liou (2005) and Maruyama et al. (2014) noted that the surface water of the Earth, which was degassed during the magma ocean period, would start to return to the mantle around 750 Ma. In the periods before 750 Ma, the water in the subducting plate returned to the surface because of higher mantle temperature (Maruyama and Okamoto, 2007), including the magma ocean phase. The water reservoirs in the lower mantle (including in the transition zone) and in the core are insignificant (Albarède, 2009) because the material cannot be transported. Therefore, the total amount of H_2O in Earth is less than 0.03% by weight, though some researchers have argued that as much as 10 M_{oce} of water can be stored in the lower mantle (e.g. Genda, 2016) and up to 80 M_{oce} in the core (Nomura et al., 2014).

Ebisuzaki and Imaeda (2016, hereafter paper I) constructed a steady-state, 1-D model of an accretion disk around a newly born star with a specified accretion rate $\dot{M}$ ranging from $10^{-6.5}$ to $10^{-8.0}$ $M_{\odot}$ yr^{-1}. They showed that the disk consists of three regions: the outer turbulent region (OTR), the magneto-rotational instability (MRI) suppressed region (MSR), and the inner turbulent region (ITR). Then, they showed that the MSR can be separated in the vertical direction into a quiet area (QA) and turbulent envelopes (see Fig. 1). This picture is consistent with the recent comprehensive review by Armitage (2011). Paper I also found that planet formation actively occurs near the OTR-MSR and MSR-ITR boundaries in the disk model with $\dot{M} = 10^{-7.0}$ $M_{\odot}$yr^{-1}. This quantitative model of planet formation was named as the "tandem planet formation" regime because there are two distinct sites for planetary formation in the disk.

This new framework may relax the difficulties faced by previous solar system formation models discussed above. First, because the planets form in two physically separated sites (the outer MRI front near ~10 AU and the inner MRI front near ~1 AU), it might naturally explain the gap in the distribution of solid material. Second, pebbles are continuously supplied to the formation sites from the outer regions via drift due to the interaction with gas. This results in the formation of fewer large bodies, as shown by Levison et al. (2015). Finally, the temperature of the formation site for rocky planetesimals at the inner MRI front is >1000 K. The rocky planetesimals are therefore expected to lose volatile components including water. This is consistent with the volatile depletion in the terrestrial planets described above. The current volatile components are then added after the solidification of the surface of Earth (Albarède, 2009).

Observational data show that the accretion rates of young stellar objects (with ages of 10^5–10^7 years) range from 10^{-10} to 10^{-5} $M_{\odot}$ yr^{-1} for T-Tauri stars and from 10^{-8} to 10^{-4} $M_{\odot}$ yr^{-1} for class 0/1 stars, which are objects hidden in the dense molecular cloud cores surrounding them (Calvet et al., 2005; Spezzi et al., 2012; Beltrán and de Wit, 2016). Most of the observational data are well represented by simple exponential functions with an e-folding time τ_a, where τ_a ranges 10^5–10^7 years and the total accretion mass (time integration of $\dot{M}$) is 1 $M_{\odot}$ (Fig. 2).

In the present paper, we study tandem planet formation in a variety of disks with different accretion rates to investigate the

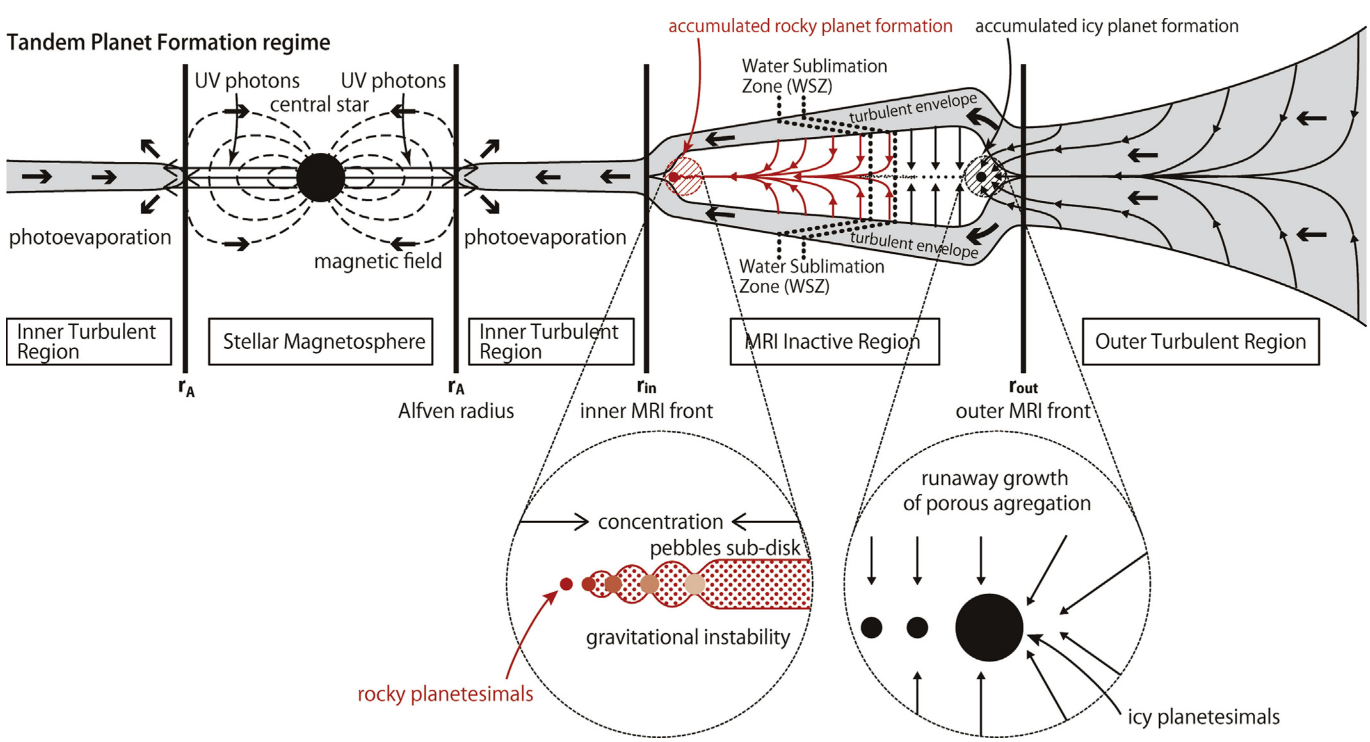

Figure 1. Schematic cross section of the protoplanetary disk proposed in paper I for the tandem planet formation regime. See text for details.

Please cite this article in press as: Imaeda, Y., Ebisuzaki, T., Tandem planet formation for solar system-like planetary systems, Geoscience Frontiers (2016), http://dx.doi.org/10.1016/j.gsf.2016.06.011