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N-body Simulations of Planet Formation

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Abstract. Accretion from many small planetesimals to planets is reviewed. Solid protoplanets accrete through runaway and oligarchic growth until they become isolated. The isolation mass of protoplanets in terrestrial planet region is about 0.1-0.2 Earth mass, which suggests giant impacts among the protoplanets in the final stage of terrestrial planet formation. On the other hand, the isolation mass in Jupiter's and Saturn's orbits is about a few to 5 Earth masses, which may be massive enough to trigger gas accretion onto the cores. The isolation mass in Uranus and Neptune's orbits is as large as their present cores. Extending the above arguments to extrasolar planetary systems that are formed from disks with various initial masses, we also discuss diversity of extrasolar planetary systems.

1. Introduction

In the conventional model of the Solar system formation (e.g., Safronv 1969, Wetherill 1980, Hayashi et al. 1986), planets are formed through accretion of planetesimals with initial sizes $\sim$ 1-10 km in a protoplanetary disk with total mass $\simeq$ 0.01-0.02$M_\odot$. The mass fraction of solid component is about 1% of the total mass. As a result of the accretion, terrestrial planets and solid cores of Jovian planets are formed. Planetesimal accretion proceeds through runaway and oligarchic growth (section 2), until large runaway planetesimals ("protoplanets") become isolated from each other.

The isolation mass of protoplanets in terrestrial planet region is about 0.1-0.2 Earth mass (section 3), which requires giant impacts among the protoplanets in the final stage of terrestrial planet formation. The giant impacts may result in formation of Moon (see, the article by Kokubo & Ida in this volume). We suggest the importance of damping of velocity dispersion due to planet-disk gravitational interactions; dissipation of disk gas may trigger orbital crossing and giant impacts, and the damping due to residual disk may account for nearly circular orbits of present Earth and Venus (section 4). Thus, the accretion of

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terrestrial planets consists of three stages: (i) runaway growth, (ii) oligarchic growth, and (iii) giant impacts.

In general, larger solid protoplanets are formed in outer region. If a solid protoplanet becomes large enough ($\simeq$ a few-$10M_{\oplus}$), pressure gradient of planetary atmosphere no more supports the atmosphere against planetary gravity and gas accretion onto the protoplanet (solid core) starts, so that a gas giant planet is formed (e.g., Mizuno 1980, Bodenheimer & Pollack 1986). The isolation mass in Jupiter and Saturn's orbits is about a few to 5 Earth masses, which may be massive enough to trigger gas accretion onto the cores (section 5). The isolation mass in Uranus' and Neptune's orbits is as large as their present core mass. However, Uranus and Neptune may have missed sufficient gas accretion, because their cores were formed after significant fraction of disk gas was depleted. The lifetime of disks is inferred as $\sim 10^7$ years from observations (Strom et al. 1993, Beckwith & Sargent 1993, Zuckerman et al. 1995). Jovian planet cores may accrete through runaway growth (and possibly oligarchic growth) without giant impact stage.

Applying the above scenario to extrasolar planetary systems with different initial disks, we also discuss diversity of planetary systems (section 6). Observationally inferred disk masses range from $10^{-3}M_{\odot}$ to $0.3M_{\odot}$ with a peak at $\sim 0.03M_{\odot}$ (Beckwith & Sargent 1996). The difference in disk mass results in different isolation masses, leading to different number of giant planets and their formation site, which causes diversity of planetary systems.

2. Runaway and Oligarchic Accretion

The first accretion stage is runaway growth, which means that the largest planetesimals grow more rapidly than the others and "run away" from the continuous mass distribution of planetesimals (e.g., Wetherill & Stewart 1989, Kokubo & Ida 1996). Runaway growth occurs as follows: (i) Dynamical friction makes velocity dispersion (orbital eccentricities and inclinations) of larger planetesimals smaller than those of smaller planetesimals (e.g., Stewart & Wetherill 1988, Ida & Makino 1992), (ii) gravitational focusing is more effective for the larger planetesimals, and (iii) as a result, the largest planetesimals grow more rapidly than the others (e.g., Wetherill & Stewart 1989, Kokubo & Ida 1996). We call these largest bodies "protoplanets".

When a protoplanet becomes massive enough to pump up the velocity dispersion of small planetesimals in the vicinity of the protoplanet, runaway accretion of the protopolanet would slow down (Ida & Makino 1993), and next runaway bodies formed in other regions catch up with the largest protoplanet. But, the mass ratio between the protoplanets and planetesimals in their vicinity keeps increasing. As a result, a two-component system of small number of similar-sized protoplanets and large number of small planetesimals forms (Kokubo & Ida 1998, 2000). In this system, "orbital repulsion" between protoplanets, which is caused by a coupling effect of distant perturbations between protoplanets and dynamical friction of small planetesimals (Kokubo & Ida 1995), results in almost equal orbital spacing of protoplanets $\simeq 10r_{\rm H}$, where $r_{\rm H}$ is the Hill radius of a protoplanet (with mass M at semimajor axis a) defined by $(M/3M_{\odot})^{1/3}a$ (Kokubo & Ida 1998, 2000). This second accretion stage is called "oligarchic growth".

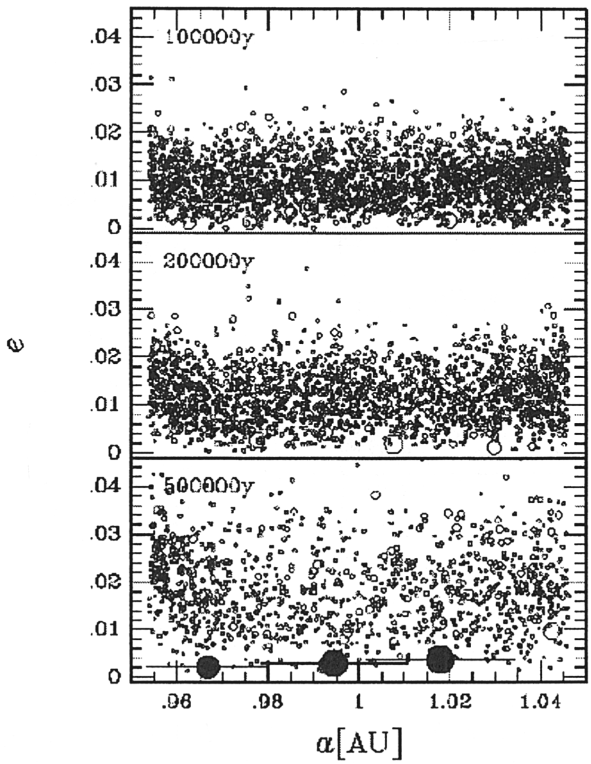

Figure 1. Snapshots of an N-body simulation of planetary accretion, starting from 4,000 planetesimals with 2×10^{23}g ($\Sigma_s \simeq 10$ gcm^{-2}). e is orbital eccentricity and a is semimajor axis. The sizes of circles are proportional to cubic root of masses (that is, proportional to physical sizes if internal density is constant). The bars in the bottom panel represent $5r_H$ in both sides of each protoplanet. (after Ida & Kokubo 2001)

In Figure 1, time evolution of masses and orbits of planetesimals are shown, where e is orbital eccentricity and a is semimajor axis of planetesimals. The sizes of circles are proportional to physical radii of planetesimals. The evolution is calculated by a three-dimensional N-body simulations (e.g., Kokubo & Ida 1996, 1998). We found orbital inclination is $\sim 0.5e$ (in radian). We started calculations with 4,000 planetesimals with 2×10^{23}g in the region from 0.95AU to 1.05AU. Mean surface density is $\simeq 10$ gcm^{-2}, which is 50% larger than that in the minimum mass disk model (Hayashi 1981). We assume 2 gcm^{-3} as internal density of planetesimals. Hydrodynamic gas drag (Adachi et al. 1976) is included. Perfect accretion is assumed: if two planetsimals contact, we create a merged body, neglecting fragmentation. The perfect accretion model would be valid except for collisions between small planetesimals with high velocities that are pumped up by the protoplanets after runaway growth.

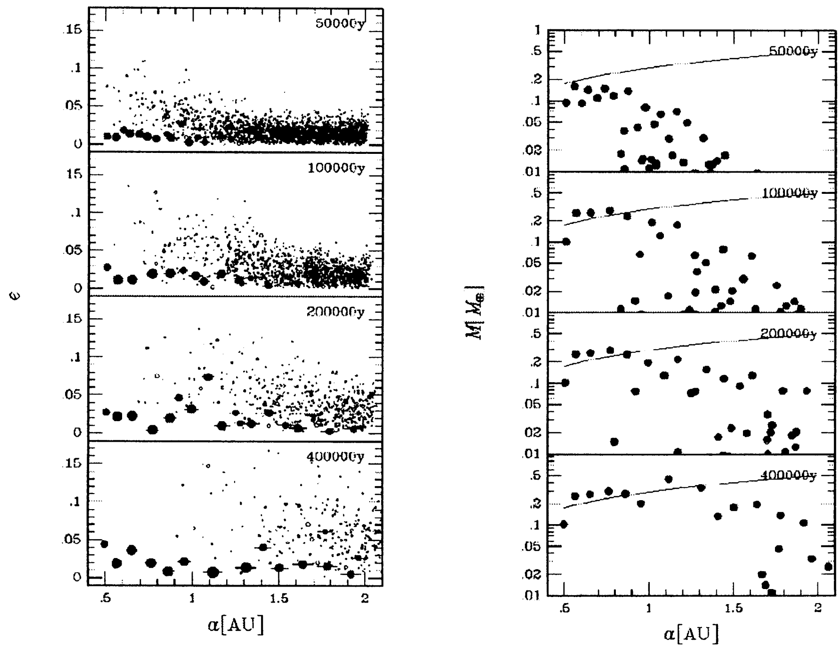

Figure 2. (left panel) Snapshots of an N-body simulation of planetary accretion in a-e plane, starting from 10,000 planetesimals with 2×10^{24}g. Σ_s is given by Eq.(2). Physical radii are artificially enlarged by a factor 10. (right panel) Snapshots in a-M plane. Analytical estimation of isolation masses given by Eq.(1) and $\Delta a = 15 r_H$ is shown by solid curves. (after Ida & Kokubo 2001)

In the upper panel at 100,000 years, a few runaway bodies appear. In the bottom panel at 500,000 years, three almost equal-sized large protoplanets (marked by filled circles) dominate the system. The masses of the protoplanets are about a few times 10^{26}g. The bars attached to the protoplanets represent $5r_H$ length in both sides. The orbital separation distance between the protoplanets are almost $\simeq 10r_H$. Since orbital eccentricities of the protoplanets are kept small by dynamical friction from small planetesimals, the orbits of the protoplanets do not cross each other. The separation with $\simeq 10r_H$ is large enough to diminish distant secular perturbations between the protoplanets. Thus, the protoplanets are orbitally isolated from each other. The orbital configuration would remain unchanged until most of planetesimals accrete to the protoplanets.

3. Isolation of Protoplanets

the mass of the protoplanets when they become isolated and all the planetesimals accrete to them is estimated for given orbital separation distance Δa and surface density of solid component Σ_s. We call such mass as "isolation mass" ($M_{\rm iso}$),

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and it is given by the equation $2\pi a \Delta a \Sigma_s = M_{iso}$ with $\Delta a \simeq 10(M_{iso}/3M_\odot)^{1/3}a$. The estimated isolation masses are (Kokubo & Ida 1998)

$$M_{iso} \simeq \begin{cases} 0.2 \times \left(\dfrac{\Sigma_s}{1.5\Sigma_{s,min}}\right)^{3/2} \left(\dfrac{a}{1AU}\right)^{3/4} \left(\dfrac{\Delta a}{10r_H}\right)^{3/2} M_\oplus & [E] \\ 5 \times \left(\dfrac{\Sigma_s}{1.5\Sigma_{s,min}}\right)^{3/2} \left(\dfrac{a}{10AU}\right)^{3/4} \left(\dfrac{\Delta a}{10r_H}\right)^{3/2} M_\oplus, & [J] \end{cases} \quad (1)$$

where $M_\oplus$ is Earth's mass, [E] and [J] denote the terrestrial planet region inside snow boundary ($a \lesssim 2.7$AU) and Jovian planet region beyond snow boundary ($a \gtrsim 2.7$AU), and $\Sigma_{s,min}$ is Σ_s in the minimum-mass disk model, given by (Hayashi 1981)

$$\Sigma_{s,min} = \begin{cases} 7(a/1AU)^{-3/2}\ \mathrm{gcm}^{-2} & [E] \\ 30(a/1AU)^{-3/2}\ \mathrm{gcm}^{-2} & [J]. \end{cases} \quad (2)$$

The corresponding orbital separation Δa between protoplanets are

$$\Delta a \simeq \begin{cases} 0.07 \times \left(\dfrac{\Sigma_s}{1.5\Sigma_{s,min}}\right)^{1/2} \left(\dfrac{a}{1AU}\right)^{5/4} \left(\dfrac{\Delta a}{10r_H}\right)^{3/2} \mathrm{AU} & [E] \\ 1.7 \times \left(\dfrac{\Sigma_s}{\Sigma_{s,min}}\right)^{1/2} \left(\dfrac{a}{10AU}\right)^{5/4} \left(\dfrac{\Delta a}{15r_H}\right)^{3/2} \mathrm{AU}. & [J] \end{cases} \quad (3)$$

Note that M_{iso} increases with a. In addition to gradual increase, it increases abruptly at 2.7 AU by the condensation of icy materials. Hence, formation of gas giants is favored in relatively outer regions (section 5).

To confirm the above estimation, we carried out an N-body simulation of planetary accretion in wider range than that in Figure 1, which covers the entire regions of terrestrial planets (0.5 AU to 2.0 AU). The results are shown in Figures 2a and 2b. We started from 10,000 planetesimals with 2×10^{24}g. Surface density of solid materials (Σ_s) is $1.5\Sigma_{s,min}$. Hydrodynamic gas drag is neglected and physical radii are artificially enlarged by a factor 10, so that accretion time scale is reduced by a factor about 10 (Kokubo & Ida 1996).

Accretion proceeds from small a to large a, because spatial density and Keplerian frequency are higher at smaller a. The mass evolution is shown more explicitly in Figure 2b, The analytical estimation of isolation masses given by Eq.(2) with $\Delta a = 15r_H$ is shown by solid curves. We found $\Delta a = 15r_H$ is more consistent with the numerical results than $\Delta a = 10r_H$, maybe because collisions between protoplanets, which we discuss in the next section, already started to some degree. Except for this point, the numerical results agree well with the analytical estimation based on oligarchic growth.

4. Terrestrial Planet Formation

The estimated isolation mass of protoplanets in the terrestrial planet region is significantly smaller than present masses of Earth or Venus. The orbital separation distance between the present terrestrial planets is much larger than the predicted $\simeq 10r_{\rm H}$. These facts require further accretion among the protoplanets. Although the isolated protoplanets may be orbitally stable on time scales of runaway and oligarchic growth, orbital eccentricities may be pumped up on longer time scales by distant perturbations between protoplanets (Chambers et al. 1996), perturbations by Jovian planets (Chambers & Wetherill 1998, Ito & Tanikawa 1999), or sweeping secular resonances during disk gas depletion (Nagasawa et al. 2000), so that orbit crossing would start. The final accretion stage of terrestrial planets may be giant impact stage.

Chambers & Wetherill (1998) and Agnor et al. (1999) pointed out that eccentricities of formed planets are much higher than those of present Earth and Venus (~ 0.01). This would be because collisional damping is not strong enough to diminish the high eccentricities that are needed for orbital crossing.

Hence, we need to consider another damping mechanism. Kominami & Ida (2001) carried out N-body simulations in the final giant impact stage, including eccentricity damping by tidal interactions with a gas disk (Ward 1993, Artymowicz 1993). The effect of the tidal interactions is essentially the same as damping by dynamical friction of residual planetesimals (Stewart & Wetherill 1988, Ida & Makino 1992), as discussed by Kominami & Ida (2001). The eccentricity damping time scale for a protoplanet with mass M at heliocentric distance r in the disk with gas surface density $\Sigma_{\rm g}$ is given by (Ward 1993, Artymowicz 1993)

$$T_{\rm damp} \sim \tau_{\rm damp} \left(\frac{M}{0.2M_\oplus}\right)^{-1} \left(\frac{r}{1\rm AU}\right)^{2} \tag{4}$$

with

$$\tau_{\rm damp} = 2500 \left(\frac{\Sigma_{\rm g}}{\Sigma_{\rm g,min}}\right)^{-1} \text{ years.} \tag{5}$$

where $\Sigma_{\rm g,min}$ is the gas surface density in the minimum-mass disk model (Hayahi 1981).

Kominami & Ida (2001) performed N-body simulations of initially isolated protoplanets with $0.2M_\oplus$, directly including the damping forces corresponding to tidal interactions with a gas disk. When $\Sigma_{\rm g} \lesssim 0.01\Sigma_{\rm g,min} \sim \Sigma_{\rm s}$, the dependence on $\Sigma_{\rm g}$ in Eq. (5) may be different, which has not been studied in detail yet. Hence they used $\tau_{\rm damp}$ (the damping time scale for a protoplanet with mass $0.2M_\oplus$ at 1AU) as a parameter, rather than $\Sigma_{\rm g}$. If $\tau_{\rm damp}$ is too short, orbit crossing is suppressed before enough collisions between protoplanets occur to make planets as large as Earth or Venus. On the other hand, if $\tau_{\rm damp}$ is too long, the pumped-up eccentricities are not reduced enough within disk life time $T_{\rm disk}$; $T_{\rm disk} \sim 10^7$ years (Strom et al. 1993, Beckwith & Sargent 1993, Zuckerman et al. 1995). With some range of damping time scale, $\tau_{\rm damp} \sim 10^7$ years, the pumped-up eccentricities decrease to the order of 0.01 within $T_{\rm disk}$ after some planets become as large as Earth or Venus.

In a real system, $\tau_{\rm damp}$ increases with time from the value ~ 2500 years to infinity maybe on a time scale $\sim T_{\rm disk}$. Iwasaki et al. (2001a, b) showed that orbital crossing of protoplanets starts when $\tau_{\rm damp}$ becomes larger than 0.1-0.3 times the time scale to start the orbital crossing in gas free environment, $T_{\rm cross}$. Because the protoplanet system should be stable on time scales of runaway and oligarchic growth, $T_{\rm cross} \gtrsim 10^5$-$10^6$ years. Hence, the evolution in the real

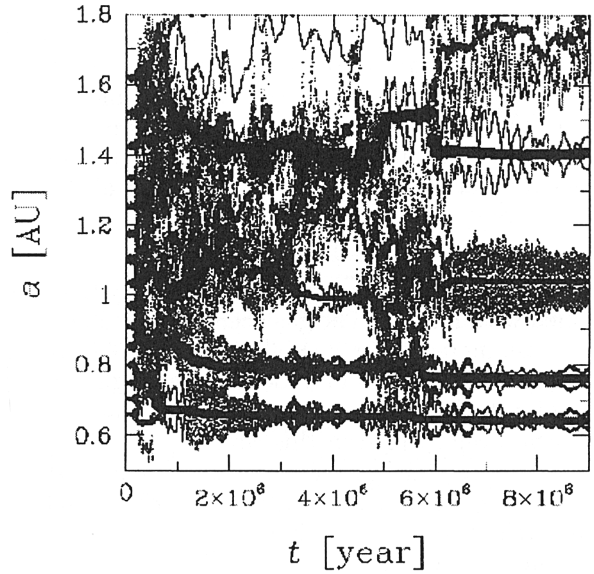

Figure 3. Accretional evolution of protoplanets. Initially, 15 protoplanets with $M = 0.2M_\oplus$ and $e, i = 0.001$ are distributed with $\Delta a = 10r_{\rm H}$. Thick lines are semimajor axes; line width expresses the masses of the protoplanets. Thin lines express pericenter or apocenter, so that separation between the lines expresses orbital eccentricity. The time-dependent damping force is included as Eq.(6). At $t = 10^7$ years, two large planets with $0.8M_\oplus$ and $0.6M_\oplus$ are formed at 0.94 AU and 0.72 AU, respectively. Their eccentricities are reduced to $\lesssim 0.01$. The other bodies remain small.

system would be like the result in Fig. 3. In Fig. 3, protoplanets with mass $0.2M_\oplus$ are initially placed with orbital separations $10r_{\rm H}$ with sufficiently small orbital eccentricities and inclinations. The damping time scale is changed as

$$\tau_{\rm damp} = 2.5 \times 10^5 \exp\left(\frac{t}{3 \times 10^6 \text{years}}\right) \text{ years.} \tag{6}$$

In the first 4×10^6 years, the damping is strong enough to prevent the protoplanets from starting orbital crossing. At $t \gtrsim 4 \times 10^6$ years, $\tau_{\rm damp}$ becomes longer than 0.1-0.3$T_{\rm cross}$ to start orbital crossing. During orbital crossing on several 10^6 years, the protoplanets collide with each other, resulting in two large planets ($0.8M_\oplus$ at 0.94 AU and $0.6M_\oplus$ at 0.72 AU). Until $t = 10^7$ years, their eccentricities becomes $\lesssim 0.01$.

Thus, formation of terrestrial planets may be regulated by depletion of disk gas. Note that depletion of residual planetesimals caused by accretion of protoplanets may also play a similar role, becuase velocity dispersion of a protoplanet is also damped by dynamical friction from residual planetesimals.

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5. Formation of Gas Giant Planets

Since planetesimal accretion is heat source to support planetary atmosphere against planetary gravity, gas accretion onto a solid core starts when solid core accretion time scale becomes longer than contraction time scale T_c of planetary atmosphere. When the core becomes isolated, planetesimal accretion stops and instantaneous core accretion time scale becomes formally infinity. Hence gas accretion onto the core starts. T_c is given by (Ikoma et al. 2000)

$$T_c \sim 10^8 (M_{\rm iso}/M_\oplus)^{-2.5} \text{ years.} \tag{7}$$

If $M_{\rm iso}$ is relatively small, gas accretion proceeds so slowly that a gas giant planet is not actually formed within $T_{\rm disk}$. The gas accretion becomes increasingly rapid as total planetary mass increases (e.g., Pollack et al. 1996, Ikoma et al. 2000). Equations (1) and (7) show that T_c may be short enough for the isolated cores in Jovian planet region to become gas giants within $T_{\rm disk} \sim 10^7$ years. Jupiter and Saturn could have been formed in this way.

$M_{\rm iso}$ is large enough to start gas accretion in Uranus and Neptune regions. However, since they are located at large a, core accretion time scales ($T_{\rm grow}$) to become $M_{\rm iso}$ would well exceed $T_{\rm disk}$. Thus they would have missed significant gas accretion, resulting in present Uranus and Neptune that have gas envelope with only $\simeq M_\oplus$.

"Orbital repulsion" would occur also during mass increase by gas accretion and it is expected that distances between gas giants also become 10-15$r_{\rm H}$, which is consistent with the orbital spacing of the present Jovian planets (Kokubo & Ida 1998).

6. Diversity of planetary systems

So far, 70 extrasolar planets have been detected (e.g., http://exoplanets.org/). One thirds of them are short-period planets with semimajor axis $\lesssim 0.1$AU, and most of residual ones have eccentric orbits. Only a few have similar orbits to those of Jupiter and Saturn (almost circular and semimajor axis $\gtrsim 1$AU). Here we discuss diversity of planetary systems, based on the above arguments.

As shown in Eq.(1), isolation masses depend on Σ_s. Beckwith & Sargent (1996) suggest Σ_s would have distribution from $\sim 0.1\Sigma_{\rm s,min}$ to $\sim 10\Sigma_{\rm s,min}$, if the a-dependence of Σ_s is similar to that of the minimum-mass disk model. (Note that $\Sigma_{\rm s,min}$ is the minimum surface density for our Solar system; Σ_s can be smaller than $\Sigma_{\rm s,min}$.) Planetary systems from disks with different initial masses would show different configuration of planets, in particular, giant planets.

Let $M_{\rm cr}$ be the critical isolated core mass defined by $T_c \simeq T_{\rm disk}$. A gas giant is formed if $M_{\rm iso} > M_{\rm cr}$ and $T_{\rm grow} < T_{\rm disk}$. In a light disk with small Σ_s, $M_{\rm iso}$ is small. In the case of $\Sigma \sim 0.1\Sigma_{\rm s,min}$, for example, $M_{\rm iso} \sim 0.2M_\oplus$ even at $a \sim 10$AU, which is well below $M_{\rm cr}$. At smaller a, $M_{\rm iso}$ is further smaller. At larger a, $M_{\rm iso}$ could become larger than $M_{\rm cr}$. However, $T_{\rm grow}$ would be longer than $T_{\rm disk}$, since $T_{\rm grow}$ is proportional to Σ_s^{-1}. Therefore, gas giants would not be formed at all in a light disk with, say, $\Sigma_s \lesssim \Sigma_{\rm s,min}/5$ (total disk mass $M_{\rm disk} \lesssim 0.003M_\odot$). In this system, many relatively small solid planets would be formed (note that Δa is also small (Eq.3)).

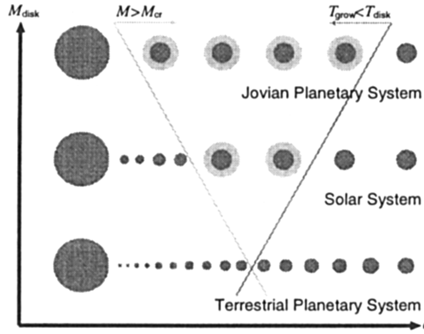

Figure 4. Schematic diagram of diversity of planetary system. For details, see text. (after Ida & Kokubo 2001)

On the other hand, in a massive disk, several gas giants would be formed. In the case of $\Sigma \sim 10\Sigma_{s,min}$, $M_{iso} \simeq 6M_{\oplus}$ at 1AU, which is enough for gas accretion within T_{disk} (Eq.(7)). Also, in a massive disk, solid core accretion is so fast that the core mass becomes $\gtrsim M_{cr}$ within T_{disk} even at large a. Therefore, several gas giants would be formed in the regions from small a to large a in relatively massive disks with, say, $\Sigma_s \gtrsim 5\Sigma_{s,min}$ (total disk mass $M_{disk} \gtrsim 0.1M_{\odot}$).

In the case of $\Sigma \sim \Sigma_{s,min}$, a planetary system similar to the Solar system, where one or two gas giants are formed beyond snow boundary, is expected. Schematic diagram of predicted diversity of planetary systems is shown in Figure 4.

The several gas giants formed in a massive disk might become orbitally unstable against long-term mutual distant perturbations (Chambers et al. 1996). After ejection of some planets or merging events, orbitally stable planets in eccentric orbits would remain, which may account for observed extrasolar planets in eccentric orbits (Weidenschilling & Marzani 1996, Lin & Ida 1997). Also, interactions between gas giants and a residual relatively massive disk may lead to significant orbital decay to a cental star (e.g., Lin & Papaloizou 1993), which may correspond to extrasolar planets with short orbital periods (Lin et al. 1995).

At present, detection probability of extrasolar planets around sun-like stars is 5% or less. Most of extrasolar planets so far discovered have relatively small semimajor axes and large masses by obsevational bias of radial velocity measurement. These extrasolar planetary systems may correspond to the planetary systems formed in significantly massive disks. The other disks with smaller masses, which are the majority of the disks, may form Solar-system-like planetary systems or ones with only terrestrial planets, if planetary formation is not inhibited by other processes such as inhibition of planetesimal formation due to turbulence in a disk (e.g., Weidenschilling 1984) or too rapid planet migration induced by tidal interactions with a disk (Ward 1986, 1997).

7. Summary

Terrestrial planets and solid cores of Jovian planets accrete from planetesimals. The model of oligarchic growth followed by runaway growth predicts the isolation

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masses of protoplanets: $\simeq 0.1$-$0.2M_\oplus$ in the terrestrial planet region and ~ 3-$10M_\oplus$ in the Jovian planet region. In the terrestrial planet region, long-term orbital instability would result in the final accretion stage of giant impacts among protoplanets. Disk-planet tidal interactions can diminish the eccentricities of Earth-sized planets formed through the giant impacts even when disk gas is so depleted that enough accretion to form Earth-sized planets is allowed. Hence, a planetary system similar to the present terrestrial planets can be formed, if disk-planet tidal interactions are considered.

In the Jovian planet region, comparison of $T_{\rm grow}$ and $T_{\rm c}$ with $T_{\rm disk}$ may explain formation of gas giants, Jupiter and Saturn, and solid giants without massive gas envelope, Uranus and Neptune.

Extending the above arguments, planetary systems formed from various initial disk masses are discussed. We define an "initial" disk as the disk at the stage when planetesimals with $\sim$ 1-10 km are born, which may correspond to disks around WTTS (Weak-line T Tauri Stars), whose ages are 10^6-10^7 years. Since disk masses of CTTS (Classical T Tauri Stars), whose ages are 10^5-10^6 years, and WTTS show no clear dependence on stellar age up to 10^7 years (e.g., Beckwith & Sargent 1996), we consider the observed disk mass distribution of CTTS and WTTS as "initial" disk masses for planet formation: inferred disk masses range from $10^{-3}M_\odot$ to $0.3M_\odot$ with a peak at $\sim 0.03M_\odot$ (Beckwith & Sargent 1996).

A massive disk ($M_{\rm disk} \gtrsim 0.1M_\odot$) may form systems similar to the extrasolar planets so far discovered, planets in eccentric orbits or very short-period planets. A light disk ($M_{\rm disk} \lesssim 0.003M_\odot$) may form a planetary system consisting of only terrestrial planets. A moderate disk with mass similar to the minimum-mass disk for Solar system may form a planetary system similar to the Solar system.

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