FORMATION OF PROTOPLANETS FROM MASSIVE PLANETESIMALS IN BINARY SYSTEMS

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ABSTRACT

More than half of all stars reside in binary or multiple star systems, and many planets have been found in binary systems. From a theoretical point of view, however, whether or not the planetary formation proceeds in a binary system is a very complex problem, because secular perturbation from the companion star can easily stir up the eccentricity of the planetesimals and cause high-velocity, destructive collisions between planetesimals. Early stages of the planetary formation process in binary systems have been studied by a restricted three-body approach with gas drag, and it is commonly accepted that accretion of planetesimals can proceed due to orbital phasing by gas drag. However, the gas drag becomes less effective as the planetesimals become more massive. Therefore, it is uncertain whether the collision velocity remains small and planetary accretion can proceed once the planetesimals become massive. We performed $N$-body simulations of planetary formation in binary systems, starting from massive planetesimals of size $\sim 100–500$ km. We found that the eccentricity vectors of planetesimals quickly converge to the forced eccentricity due to the coupling of the perturbation of the companion and the mutual interaction of planetesimals, if the initial disk model is sufficiently wide in radial distribution. This convergence decreases the collision velocity, and as a result accretion can proceed much in the same way as in isolated systems. The basic processes of the planetary formation, such as runaway and oligarchic growth and final configuration of the protoplanets, are essentially the same in binary systems and single star systems, at least in the late stage, where the effect of gas drag is small.

Subject headings: binaries: close — methods: $n$-body simulations — planetary systems: formation

1. INTRODUCTION

As of 2007 March 21, 513 candidates of extrasolar planets have been found, and at least 30 of them are in binary or multiple star systems (Raghavan et al. 2006). Table 1 shows the candidates for close binary or multiple star systems with planets. In this table, $\gamma$ Cephei is an example of a close binary systems in which we are interested. According to Hatzes et al. (2003), the semimajor axis and eccentricity of the companion star of $\gamma$ Cephei are 18.5 and 0.36 AU, respectively. The planetary formation process in such a close binary system is the main target of this paper. The frequency of planets in binary systems is not significantly different from that for single star systems (Desidera & Barbieri 2007). It is very important to investigate the formation process in binary system, because more than half of stars reside in binary or multiple star systems.

Many authors have investigated planetary accretion processes using $N$-body simulations (e.g., Araseth et al. 1993; Kokubo & Ida 1996, 1998, 2000, 2002). In all of these simulations, the evolution of protoplanetary disks around isolated stars was studied. On the other hand, Quintana et al. (2002) and Quintana & Lissauer (2006) have investigated the planet formation in binary system from protoplanets by $N$-body simulations. They studied the late stage of the planet formation process (from protoplanets to planets).

Marzari & Scholl (2000) and Thébault et al. (2004, 2006) investigated the distribution of the collision velocity between planetesimals with and without gas drag in binary systems by a restricted three-body approach. They found that orbital phasing occurred and collision velocity remained small due to the coupling of the gas drag effect and secular perturbation, and they concluded that planetary accretion could proceed. As the planetesimals become more massive, however, the gas drag becomes ineffective, and mutual gravitational effect between planetesimals becomes important. In such a condition, whether the collision velocity remains small is not clear. As stated above, the final stage, from protoplanets to planets, has been studied by $N$-body simulations, but there has been no $N$-body work on the intermediate stage, from massive planetesimals whose size is $100–500$ km to protoplanets. In this paper, we focus on this intermediate stage.

In a binary system, the orbits of planetesimals change due to perturbation from the companion. The most important term of the perturbation in our simulation region is secular perturbation, if the orbit of the companion is eccentric. The effect of secular perturbation is that the eccentricity vector moves on a “perturbation circle.” Thus, if interaction between planetesimals and gas drag are neglected, planetesimals with a different semimajor axis move on the perturbation circles on different frequencies and phases, and therefore gain high relative velocity. This is the reason why the collision velocity becomes high in previous works without gas drag or self-gravity (Marzari & Scholl 2000; Thébault et al. 2004, 2006). If the collision velocity becomes high when the planetesimals become massive, and thus the effect of gas drag becomes small, the accretion process might halt, since collisions might be destructive.

It is a very important question whether destructive collisions occur when the gravitational interaction between planetesimals is taken into account, because it determines whether the accretion process can continue after gas drag becomes ineffective. Ito & Tanigawa (2001) studied the evolution of the orbital elements of protoplanets under the perturbation of Jupiter and found that the eccentricities of the protoplanets aligned with each other, resulting in an evolution that was very similar to that without the influence...
of Jupiter. This alignment is due to gravitational interaction between the protoplanets. If this kind of alignment also occurs for planetesimals in a binary system, the collision velocity can become smaller than the value predicted by Marzari & Scholl (2000).

In this paper, we report the results of \( N \)-body simulations of protoplanet formation from massive \((3 \times 10^{23} - 1.4 \times 10^{24})\) g planetesimals. We start simulations with a planetesimal disk in which all planetesimals have the same mass. The gravitational interaction between planetesimals is included, and gas drag is neglected. We summarize the theory of secular perturbation and discuss which cases hold, and we ignore interactions between planetesimals. We start simulations with a planetesimal disk in which all planetesimals have the same mass.

### 2. THEORETICAL PREPARATION

#### 2.1. Brief Description of Secular Perturbation

If the mutual interaction of planetesimals and gas drag are negligible, the orbital evolution of a planetesimal in a binary system can be described by a restricted three-body approximation, and the time evolution of eccentricity and the longitude of pericenter of the planetesimal are given by secular perturbation theory. The secular evolution of the \( h \) and \( k \) variables of the planetesimals is expressed as (Heppenheimer 1978; Whitmire et al. 1998; Thébault et al. 2006)

\[
h(t) = e_p \sin (At + \omega_0),
\]

\[
k(t) = e_p \cos (At + \omega_0) + e_f,
\]

where

\[
h(t) = e \sin \varpi,
\]

\[
k(t) = e \cos \varpi,
\]

and \( e \) and \( \varpi \) are the eccentricity and the longitude of the pericenter of the planetesimal. Here, \( A, e_p, \omega_0, \) and \( e_f \) are constants that depend on the strength of the secular perturbation. We take the \( k \)-axis as the direction of the eccentricity vector of the companion. In other words, the eccentricity vector of the companion is \((e_f, 0)\). The semimajor axis of the companion is \( a_B \), and its mass is \( M_B \). According to the secular perturbation theory, \( e_f \) is given by

\[
e_f = \frac{5}{4} \frac{a}{a_B} \frac{e_B}{1 - e_B^2}.
\]

This \( e_f \) is forced eccentricity induced by the companion star. Here, \( a \) is the semimajor axis of the planetesimal. The angular velocity of rotation on \( k \)-\( h \) plane, \( A \), is given by

\[
A = \frac{3}{2} \pi \frac{1}{(1 - e_f^2)^{1/2} m_B} \frac{a^{3/2}}{a_B^2}.
\]

We use a system of units in which the solar mass, 1 AU and 1 yr are all unity. The remaining two constants, \( \omega_0 \) and \( e_p \), are determined from the initial orbital elements of the planetesimal. We call the vectors, \( e = (k, h) \) and \( e_f = (e_f, 0) \), the eccentricity vector and the forced eccentricity vector, respectively. On the \( k \)-\( h \) plane, the eccentricity vector of a planetesimal moves in a circle centered on \( e_f \).

#### 2.2. Initial Eccentricity of Planetesimals

We consider two types of initial conditions for planetesimals. In the first, the initial distribution of eccentricity vectors of planetesimals is centered at the forced eccentricity vector. The distributions of \( e - e_f \) and inclination \( i \) are both given by the Rayleigh distribution with dispersions \( \langle (e - e_f)^2 \rangle^{1/2} = 2 \langle (i^2)^{1/2} = 0.02 \). We call this model the “forced” model. In the second model, the distribution of eccentricity vector is centered on the origin of the \( k \)-\( h \) plane. The distributions of eccentricity \( e \) and inclination \( i \) are also given by the Rayleigh distribution with dispersions \( \langle e^2 \rangle^{1/2} = 2 \langle i^2 \rangle^{1/2} = 0.02 \). This is the same distribution as those used in previous works for the \( N \)-body simulation of planetary formation in isolated systems (Kokubo & Ida 2002). We call this model the “circular” model.

We argue that the “forced” model is more suitable for simulation in the binary system than the circular model for the following reasons. Consider a narrow region of a planetesimal disk such as the region of 0.95 AU < \( a < 1.05 \) AU. If the eccentricity vectors of planetesimals in this region do not distribute around the forced eccentricity vector, they will rotate around the position of the forced eccentricity vector. The planetesimals in a narrow region would rotate together, because the angular velocity \( A \) is similar for planetesimals with similar values of the semimajor axis \( a \). In addition, they align due to secular interactions between planetesimals (see, e.g., Ito & Tanikawa 2001). Because of this collective motion, the relative velocity between planetesimals is kept small in this narrow “ring.”

However, if we consider a wider region, it would behave as collection of many narrow rings. If we ignore interactions between the rings, they would rotate on their own angular velocities \( A \). Since neighboring rings have slightly different values of \( A \), they would...
soon physically collide with each other, resulting in damping of the “free” eccentricity. Gravitational interaction between rings would also damp the relative difference of eccentricity vectors. In other words, planetesimals in the circular model would first relax to the forced model. We argue that the equilibrium state is more suitable for the initial conditions. This is why we consider the “forced” model.

As mentioned in §1, we studied the late stage of the formation process of protoplanets. The earlier phase has been studied by Marzari & Scholl (2000) and others. Thus, it might seem reasonable to set the initial eccentricity and longitude of the pericenter of planetesimals to the equilibrium value of the orbital phasing in Marzari & Scholl (2000), instead of the circular model. However, we found that it is a bit difficult to use their results, because they adopt a circular gas disk model. This circular gas disk in a binary system with an eccentric companion seems a bit unnatural. Due to the perturbation from the companion star, the gas disk may be twisted. We could not find previous works that directly studied the equilibrium state of the gas disk under the secular perturbation of a companion, but recent work by Papaloizou (2005) seems to imply that the eccentric disk can be long lived, even if there is no companion. So it seems likely that the gas disk is not circular when an eccentric companion exists. This may change the gas drag effect to the planetesimals and might affect the direction of the orbital phasing. This is the reason why we do not use Marzari & Scholl’s results. Even if the orbital elements are correct, our circular model’s results are very close to their own, and it would soon relax to the forced model. We argue that the equilibrium state is more suitable for the initial conditions. This is why we consider the “forced” model.

We adopt three models for the companion. Model alpha corresponds to the \( \alpha \) Cen system. The mass ratio is chosen to be the same as that of the \( \alpha \) Cen system, (1.1 : 0.9). For the other two models we use a somewhat smaller semimajor axis than those of observed binary systems in which the planets are found. We choose this value to study the case in which secular perturbation is strong. For circular models we use an axisymmetric surface mass density distribution for a planetesimal disk whose surface mass density is given by

\[
\Sigma_{\text{solid}} = \Sigma_0 \left( \frac{a}{1 \text{ AU}} \right)^{-3/2} \text{ g cm}^{-2},
\]

where \( a \) is distance from the primary star, and \( \Sigma_0 \) is the reference surface density at 1 AU (we adopt \( \Sigma_0 = 10 \text{ g cm}^{-2} \)). Table 3 shows the model parameters. Here, \( N \) is the number of planetesimals. For radial distribution we use two-disk models, “wide-disk” models (models 0–5) and “narrow-disk” models (models 6–8). In the “wide-disk” models we set inner and outer cutoff radii to 0.5 and 1.5 AU, respectively. In the “narrow-disk” models, inner and outer cutoff radii are 0.95 and 1.05 AU, respectively. Planetesimals have equal mass in all models. The number of planetesimals is 10,000 in the wide-disk models. In two narrow-disk models (models 6 and 7) the number of planetesimals is 5000. In one of the narrow-disk models (model 8) the number of planetesimals is 975. This is a “cutoff” model that has the planetesimals of the same mass as in the wide-disk models. The density of planetesimals is 2 g cm\(^{-3}\). We increased their radii by a factor 5 to accelerate the accretion process (Kokubo & Ida 1996). At first, all planetesimals had the same mass (\( \geq 1.44 \times 10^{24} \text{ g} \) in models 0–5 and 8 and \( 2.88 \times 10^{23} \text{ g} \) in models 6 and 7).

One critical question is if our “same-mass” setup can be really regarded as the description of the later stage of planetary formation. Recent theoretical and numerical works on planetary accretion (e.g., Inaba et al. 2001; Rafikov 2003) seem to suggest that the “orderly” phase of growth does not exist, and runaway growth starts from a much smaller mass than that of our setup. Our setup, therefore, is not realistic. However, statistical calculations by Inaba et al. (2001) have shown that once massive planetesimals \( (M \geq 10^{23} \text{ g}) \) have formed, planetesimals with a mass less than \( 10^{21} \text{ g} \) become dynamically unimportant. So, even though our initial condition is oversimplified, it might still give a qualitatively valid description of the later phase.

Two planetesimals are considered to collide when their distance becomes less than the sum of their radii. We assume a perfect accretion scenario under which planetesimals always accrete when they collide. Whether or not this assumption is good depends on the distribution of the collision velocities. The escape velocity of
our planetesimals is $200 - 600$ m s$^{-1}$ and is of the same order as the initial collision velocity. Furthermore, if the gas effect is included, the eccentricity dispersion might be less than our estimate, and the collision velocity becomes smaller. So, we believe that the assumption of perfect accretion is valid.

As stated above, we increased the radii of planetesimals $f$-fold (here, $f = 5$) to save calculation time. This acceleration of accretion may affect the time evolution of planetesimals, especially the time evolution of orbital elements on the $k$-$h$ plane, because the increase of radii changes the timescale of accretion but does not affect secular perturbation of the companion star.

3.2. Integration Scheme

We use the fourth-order Hermite scheme (Makino & Aarseth 1992), with hierarchical time steps (Makino 1991) improved for planetary systems (Kokubo et al. 1998), for numerical integration of planetesimals and the companion star. The equation of motion for planetesimals is given by

$$a_i = - \sum_{ij} G m_i r_{ij} - G (m_i + M_p) r_{i} r_p G M_\odot \left( \frac{r_{ic}}{r_{ic}^3} + \frac{r_{pc}}{r_{pc}^3} \right),$$

(8)

where $M_p, M_\odot, r_q$, and $r_{ic}$ are the mass of the primary star, the mass of companion star, the position of planetesimal relative to the primary star, and that relative to the companion star. We use the position of the primary star as origin of the coordinate for planetesimals. The motion of the primary star due to the gravitational forces of planetesimals is neglected.

The most expensive part of the numerical integration is the calculation of mutual gravitational interaction between planetesimals. We use GRAPE-6 (Makino et al. 2003) and GRAPE-6A (Fukushige et al. 2005) to calculate the gravitational interaction between planetesimals. We also integrate the orbit of the companion star using the fourth-order Hermite scheme. For both the planetesimals and the companion stars we use the standard time step criterion (Aarseth 1985)

$$\Delta t = \sqrt{\frac{\eta |a|^3 |a^2|}{|\dot{a}|^3 |a^3| + |a^2|^2}},$$

(9)

Since the orbital period of the companion is long, the accuracy of its orbit is more than enough.

4. RESULTS

4.1. Planetary Accretion in Binary Systems

Figure 1 shows the time evolution of planetesimals of model 1 (left) and model 0 (right) on the $a$-$e$ plane. We integrated the system for $5 \times 10^5$ yr. We see that protoplanets grow in a very similar way in these two models. This behavior is essentially the same for all models.

Figure 2 shows cumulative mass distribution of planetesimals of the region $0.9 \ AU < a < 1.1 \ AU$. The time evolutions of all of these models are very similar. In all cases, the mass distributions first relax to the power-law distribution with power index $d \log n \propto \log m \sim -1.5$ (top panels), where $n_c$ is the cumulative number of planetesimals. This power-law distribution is characteristic of the runaway growth (Makino et al. 1998; Kokubo & Ida 2000).

As time goes on, the mass distributions become bimodal, forming planetesimals with mass $M \approx 1-10 \times 10^{24}$ g and large protoplanets with mass $M \approx 10^{27}$ g. This bimodal mass distribution is the result of the runaway and oligarchic growth of protoplanets (Kokubo & Ida 1996, 1998). The time evolution of the mass distribution of binary systems is almost the same as that in single star systems. It means that secular perturbation does not change the process of protoplanet formation. Runaway and oligarchic growth also occur in binary systems in a similar way as in the single star system.

In Figures 3–6, we show the evolution of the mass of most massive planetesimals (3 and 4) and the average mass of planetesimals (5 and 6). We can see that the evolution is rather similar, and there is no systematic tendency due to the presence of the companion.

The evolution of the surface mass density of model 1 ($e = 0.25$, forced) and that of model 0 (no companion) are shown in Figure 7. We found that the density profile of planetesimals in a binary system is virtually the same as that in a single star system.

From secular perturbation theory, time evolution of semi-major axis of a planetesimal is given by

$$\frac{da}{dt} = \frac{2}{na} \frac{\partial R}{\partial e},$$

(10)
where $\epsilon$ and $R$ are the mean longitude at epoch and the disturbing function, respectively. In practice, variations of $\epsilon$ can usually be neglected, since it is a small effect. Thus, mass migration does not occur, since secular perturbation hardly changes the semi-major axis of planetesimals. Our results are consistent with this theoretical expectation.

4.2. Time Evolution of Eccentricity

The time evolutions of the distribution of the planetesimals on $k$-$h$ plane of model 1 (forced model of $e = 0.25$), 3 (circular model of $e = 0.25$), 8 (cutoff model of $e = 0.25$), and 4 and 5 (circular models) are shown in Figure 8.

![Diagram showing the time evolution of the distribution of planetesimals](image)

The top three panels show models 1, 3, 8, all with an $e = 0.25$ companion. In model 1 (top panel), planetesimals are initially distributed around the forced eccentricity, and this does not change in time. In model 3, planetesimals are initially distributed around zero eccentricity, but this initial distribution is replaced by a distribution centered at the forced value. The behavior of planetesimals in model 8 is very different. The distribution after 30,000 yr is not centered at the forced value and keeps rotating around the forced eccentricity vector (see Fig. 9 and description below). This difference between narrow-disk models and wide-disk models will be discussed in more detail in § 4.2.1. The bottom two panels of Figure 8 show that the eccentricity vectors of the planetesimals of other circular models with wide distribution
also converge to the forced eccentricity vector. We will discuss
the time evolution of proper eccentricity in § 4.2.2.

4.2.1. Difference between Wide and Narrow Models

We performed simulations of the narrow-disk models (models 6, 7, and 8) to see the difference between the wide and narrow
distributions. We use two types of narrow-disk models. One has
the planetesimals of the same mass as in wide-disk models, and
thus the number of planetesimals is small ($N = 975$, model 8). The
other has a large number of smaller planetesimals (see Table 2).

Figure 9 shows the time evolution of eccentricity. In wide-
disk models, the oscillation of eccentricity is damped quickly due
to the convergence to the forced eccentricity vector, as shown in
Figure 8. In narrow-disk models, however, the eccentricity librates
around the forced eccentricity and does not converge to the forced
eccentricity.

This difference can be understood as follows. As we discussed
in § 2, the planetesimals rotate around the forced eccentricity vec-
tor on the $k$-$h$ plane, and the angular velocity $\omega$ is a function of
semimajor axis of planetesimals. In the case of narrow-disk
models, the range of $\omega$ is small, and it is possible that all plan-
etesimals synchronize due to mutual gravitational interaction.
Thus, in narrow-disk models planetesimals move collectively on
the $k$-$h$ plane. In the case of the wide-disk models, however, such
collective motion is not allowed, since the range of $\omega$ is too large.
If planetesimals with different values of $a$ (and therefore $\omega$) ro-
tate around its own values of forced eccentricity on their own
timescales, collision is enhanced and eccentricity will be damped
to forced values. Thus, oscillation of eccentricity damps quickly
in wide models.

We performed a simulation of narrow-disk models to see how
this behavior is affected by the mass of planetesimals. The bot-
tom panel of Figure 9 shows the time evolution of eccentricity of
model 8. The behavior of model 8 is almost the same as that of
model 5. Thus, the number of planetesimals or mass of each plan-
etesimal do not change the result. In narrow-disk models, the
convergence to the forced eccentricity vector never occurs.

4.2.2. Time Evolution of Proper Eccentricity

Time evolution of proper eccentricity, (i.e., the distance from
the forced eccentricity in the $k$-$h$ plane) is shown in Figure 10.
The proper eccentricity is averaged for a planetesimal with a semi-
major axis between $0.95 \text{ AU} < a < 1.05 \text{ AU}$. In circular models
(model 3, 4, and 5) the proper eccentricity quickly decreases
through collisional damping and gravitational relaxation. This
means that the eccentricity vector of the planetesimals converge to
the forced eccentricity vector. In forced models (model 1, 2) and
the single star model (model 0), on the other hand, the proper ec-
centricity does not change significantly in the early stage of the
simulation (before 40,000 yr). The convergence in model 5 ($\alpha$ Cen
model) is slower than that in the other two circular models, and
before convergence the planetary accretion has almost finished. This is because of the small angular velocity \( A \) of \( \alpha \) Cen system. However, if we adopt real radii, the convergence would probably occur before the accretion completes. The time evolution of proper eccentricity after the convergence is similar to that in the forced models and the single star model. The proper eccentricity increases in the late stage due to the viscous stirring.

Figure 11 shows the time evolution of the mass-weighted average of proper eccentricity for the same radial range as in Figure 10. In the early stage of the simulation, its behavior is similar to that of the simple average in Figure 10. However, in the late stage, the increase is slow because of dynamical friction on seeds of protoplanet. In single star systems, the eccentricity of seeds of protoplanets becomes small (i.e., the eccentricity vectors converge to the origin of the \( k-h \) plane). On the other hand, in binary systems, the eccentricity vectors converge to the forced eccentricity, and the evolution of proper eccentricity is similar to the evolution of eccentricity in the single star system. This means that the orbit of planetesimals does not become circular as in single star system, but becomes eccentric in binary systems, and their pericenter aligns to the pericenter of companion star.

The distance between planetesimals on the \( k-h \) plane determines the collision velocity. Thus, the convergence reduces the collision velocity between planetesimals. In model alpha, for example, the maximum distance between planetesimals could become 0.08 by secular oscillation if the mutual gravitational effect is neglected. It corresponds to the collision velocity of \( 3000-4000 \) m s\(^{-1}\) at 1 AU. Collision at this velocity is destructive even for the mass of the planetesimal of about \( 1.4 \times 10^{24} \) g (its escape velocity is about 600 m s\(^{-1}\)). On the other hand, the collision velocity is reduced to about 500-1000 m s\(^{-1}\) with this convergence. As we
mentioned above, gas drag affects the eccentricity dispersion of the planetesimals (i.e., gas drag cannot be negligible in this sense). The simulations in which gas drag and mutual gravitational effects are taken into account are required to determine the precise value of the collision velocity.

5. CONCLUSION AND DISCUSSION

We have performed simulations of the formation of protoplanets from massive planetesimals (with radii of 100–500 km) in close binary systems, for which gas drag effect is negligible and the coupling of the secular perturbation and gravitational interaction is important. We found that eccentricity vectors of planetesimals quickly converge to the forced eccentricity if the initial disk model is sufficiently wide in radius and secular perturbation is sufficiently strong. The eccentricity vectors of planetesimals that have heavier mass than the other planetesimals converge to the forced eccentricity more strongly. This convergence results in orbital phasing, and it reduces the value of the collision velocity to less than the value predicted in studies with a restricted three-body approach. Runaway and oligarchic growth also occur in binary systems much in the same way as in isolated star systems, at least in the late stage of formation. The final configuration of protoplanets is not different between close binary systems and isolated star systems.

Our simulations, however, have the following limitations. (1) We underestimated the effect of secular perturbation. The $\gamma$-fold change of radius increases frequency of collision and accelerates planetary accretion. This acceleration of the formation process causes relative underestimations of secular perturbation. We plan to perform the simulation with real radii of planetesimals to see if this effect would make any difference. (2) We investigated only three binary systems. More simulations of various binary systems are required to determine the quantitative relationship between the convergence of eccentricity vectors and the strength of secular perturbation. (3) We neglected the effect of gas drag. This is not a problem for the late stage, which we studied. In the earlier stage, however, gas drag is clearly important. We plan to calculate the equilibrium state of the gas disk under secular perturbations and perform simulations that include the gas effect in future works.

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