ACCRETION OF SOLID MATERIALS ONTO CIRCUMPLANETARY DISKS FROM PROTOPLANETARY DISKS

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ABSTRACT

We investigate the accretion of solid materials onto circumplanetary disks from heliocentric orbits rotating in protoplanetary disks, which is a key process for the formation of regular satellite systems. In the late stage of the gas-capturing phase of giant planet formation, the accreting gas from protoplanetary disks forms circumplanetary disks. Since the accretion flow toward the circumplanetary disks affects the particle motion through gas drag force, we use hydrodynamic simulation data for the gas drag term to calculate the motion of solid materials. We consider a wide range of size for the solid particles (10^{-2}–10^9 m), and find that the accretion efficiency of the solid particles peaks around 10 m sized particles because energy dissipation of drag with circum-planetary disk gas in this size regime is most effective. The efficiency for particles larger than 10 m becomes lower because gas drag becomes less effective. For particles smaller than 10 m, the efficiency is lower because the particles are strongly coupled with the background gas flow, which prevents particles from accretion. We also find that the distance from the planet where the particles are captured by the circumplanetary disks is in a narrow range and well described as a function of the particle size.

Key words: planets and satellites: formation – protoplanetary disks

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1. INTRODUCTION

The giant planets in our solar system have many natural satellites. In terms of mass, most of the satellites are categorized into regular satellites, which are rotating in almost circular and co-planer with the equatorial planes of the parent planet. Because of the regularity, the satellites are believed to be formed in circumplanetary disks, which would have existed when the giant planets were forming in the protoplanetary disk.

Thus the satellite systems had been considered to have formed in an isolated and closed disk that had enough mass to produce the current systems (Lunine & Stevenson 1982). This is the so-called minimum mass sub nebula (MMSN) disk model. However, the formation through such a heavy disk leads to some difficulties in its formation processes, such as too high temperature for H_2O to be in the solid phase, too fast type I migration for satellites, and a too short accretion timescale for Callisto’s internal structure not to be fully differentiated (Canup & Ward 2002).

In order to overcome these problems, two further models to describe circumplanetary disks have been proposed. One is a gas-starved disk model (Canup & Ward 2002, 2006; Ward & Canup 2010), which is an open disk model. This means that the disk receives continuous mass supply from the protoplanetary disk, and is much less massive than the MMSN-type disk. This model solves several serious problems that could not be solved by MMSN-type disk model (Canup & Ward 2002). Another approach is the solids-enhanced minimum mass (SEMM) model (Mosqueira & Estrada 2003; Estrada et al. 2009), which consists of a compact heavy component and a wide-spread less massive one. The two components are produced by the difference of specific angular momentum of inflow gas, and the difference corresponds to whether or not a gap exists along the planet orbit. An attempt was made to explain the difference of the observed moment of inertia of Ganymede and Callisto by using the large difference in surface density between the two components.

The structures of circumplanetary disks have been studied using hydrodynamic simulations. There were pioneering works that tried to observe circumplanetary disks (Miki 1982; Sekiya et al. 1987; Korycansky & Papaloizou 1996), and as computational speed became faster, the structure of the circumplanetary disks became clearer through two-dimensional simulations (Kley 1999; Lubow et al. 1999; Tanigawa & Watanabe 2002) with a nested-grid method (D’Angelo et al. 2002) and three-dimensional simulations (D’Angelo et al. 2003; Bate et al. 2003; Klahr & Kley 2006). In particular, recent simulations have revealed the circumplanetary disk structure and the accretion flow onto the disk in very high resolution with some special techniques, such as nested-grid methods in Eulerian codes (Machida et al. 2008, 2010; Paardekooper & Mellema 2008; Tanigawa et al. 2012; Gressel et al. 2013; Szulagyi et al. 2014) or smoothed particle hydrodynamics (SPH) methods (Ayliffe & Bate 2009), in addition to the recent development of high-performance computers.

However, satellites around the giant planets are made of solids, and the supply of solid material into circumplanetary disks has not been studied so far. There are some studies that considered the accretion of particles onto giant planets under the influence of gas flow in protoplanetary disks for dust- or boulder-size particles (Rice et al. 2006; Paardekooper & Mellema 2008; Tanigawa et al. 2012; Zhu et al. 2012) or planetesimals (Zhou and Lin 2007; Shiraishi & Ida 2008), but the structure of gas flow near the planet, such as circumplanetary disks, was not resolved in such studies. In the phase of giant planet growth, circumplanetary disks are rotating around the planet almost at Keplerian velocity, and the density would be much higher than that in protoplanetary disks (Ayliffe & Bate 2009; Tanigawa et al. 2012). The particle motion is thus expected to be affected significantly by the circumplanetary disks when they are captured, and therefore it is necessary to consider the high-resolution structure of the gas flow near the planet.

In this study, we examine the supply of solid material onto the circumplanetary disk by simulating the motion of particles
that are originally rotating in heliocentric orbits. In Section 2, we will explain the formulation of our model. In Section 3, the results of orbital simulation will be shown and we discuss issues that we do not address in this paper that might be important. We summarize our results in Section 5.

2. METHODS

We consider a growing giant planet embedded in a protoplanetary disk. Particles in heliocentric orbits are rotating in the protoplanetary disk. In this study, we simulate the particle motion if the particles are captured by the circumplanetary disk under the influence of the gas accretion flow onto the giant planet. We consider that the planet is rotating in a circular orbit with no inclination from the midplane of the protoplanetary disk.

2.1. Basic Equations

In order to investigate the orbits of particles around the planets in detail, we use Hill’s equation (e.g., Henon & Petit 1986; Nakazawa & Ida 1988) with a gas drag term. Hill’s equation describes the motion of small particles near a planet that is rotating around the central star, and adopts a frame rotating with a planet that is static at the origin of the coordinate on the frame. Hill’s equation is usually normalized by Hill’s radius for length, which is the inverse of the orbital angular velocity of the planet with time. The non-dimensional equation of the particles on the Hill coordinate can be written as

\[ \frac{d\tilde{v}}{dt} = -\nabla \tilde{\Phi} - 2\tilde{e}_z \times \tilde{v} + \tilde{a}_{\text{drag}}, \]

where \( e \) is the unit vector in the z-direction, \( \tilde{v} \) is velocity, \( \tilde{r} \) is time. The second term in the right-hand side is the Coriolis force, which arises from the frame rotating with the planet orbital motion. The normalized Hill potential \( \tilde{\Phi} \) is given by

\[ \tilde{\Phi} = -\frac{3}{2} \tilde{r} \tilde{r}^2 + \frac{1}{2} \tilde{z}^2 + \frac{9}{2}, \]

where \( \tilde{r} = \sqrt{\tilde{x}^2 + \tilde{y}^2 + \tilde{z}^2} \). The first term in the right-hand side corresponds to the planet potential, the second and third terms describe the tidal potential in the horizontal and vertical directions, respectively. The last constant term is added so that the potential at the Lagrange points 1 and 2 becomes zero. The acceleration due to gas drag \( \tilde{a}_{\text{drag}} \) is described by

\[ \tilde{a}_{\text{drag}} = \frac{F_{\text{drag}}/m}{r_2 \Omega_K^2} = -\frac{3}{8} C_D \tilde{\rho}_g \tilde{r}^{-1} \Delta \tilde{u} \Delta \tilde{u}, \]

where \( F_{\text{drag}} = (C_D/2)\pi r_2^2 \tilde{\rho}_g \Delta \tilde{u} \Delta \tilde{u} \) is the drag force for a particle with radius \( r_2 \), \( m \) is the mass of the particle, \( C_D \) is the non-dimensional gas drag coefficient, \( \tilde{\rho}_g \) is the gas density, \( \tilde{\rho}_s \) and \( \tilde{r}_s \) are the internal density and the normalized physical radius of the particles, and \( \Delta \tilde{u} \) is the velocity of the objects relative to the gas. Variables with tildes denote non-dimensional quantities.

2.2. Effect of Gas Flow

2.2.1. Hydrodynamic Simulation

We use the gas flow that was obtained by Tanigawa et al. (2012). In order to obtain gas flow with high resolution near the planet, they employed a three-dimensional hydrodynamic simulation with a nested grid code (Machida et al. 2005), which was originally developed to explore the star formation process through the collapse of the molecular cloud core (Matsumoto & Hanawa 2003). The nested grid technique enables them to obtain a very high resolution gas flow in the vicinity of the planet. In the calculation, they used 11 levels for the nested grid. They adopted Hill’s coordinate, which also contributes to enhance the resolution near the planet.

In their simulation, the ratio of Hill’s radius to the scale height of the protoplanetary disk, which is the only parameter of the system, was adopted to be unity. This corresponds to \( M_0 \sim 120M_E(a/5.2AU)^{3/4} \) for \( T = 280(a/1AU)^{-1/2} \) K, where \( M_E \) is Earth mass and \( a \) is the semi-major axis of the planet. The planet is assumed to be in the active gas accretion phase, which corresponds to the stage after the onset of nucleated instability (Mizuno 1980; Bodenheimer & Pollack 1986; Ikoma et al. 2000), but not to be embedded in a very deep gap.

2.2.2. Background Gas Flow

Figure 1 shows the gas density and velocity field of the flow at the midplane. In Figure 1(a), which shows the wide field flow mainly focusing outside the Hill sphere, we can see a two-arm shock structure from the Hill sphere of the planet. The shock structure corresponds to the spiral structure propagating in global (protoplanetary) disks. Figure 1(b) shows the same flow, but with enlarged view focusing around the Hill sphere. We can see that there are shocks along the lines through (\( \tilde{x}, \tilde{y} \)) \( \sim (\pm 1.5, 0) \) and (0, \( \pm 1.5 \)) where gas has discontinuity in velocity and density. Gas inside the Hill sphere shows prograde rotation. Figure 1(c) shows an even further enlarged view. In this scale (~0.1 scale height), we can see another two-arm spiral structure around the planet, but the non-axisymmetric structure disappears on an even smaller scale (~0.01 scale height), as in Figure 1(d). Note that a low density region (\( \tilde{r} \lesssim 0.005 \)) arises from the sink condition around the origin (see Tanigawa et al. (2012) in detail).

2.2.3. Gas Drag Coefficient

The gas drag coefficient \( C_D \) we adopt is an approximated formula written in the form (Watanabe & Ida 1997):

\[ C_D \simeq \left[ \left( \frac{24}{R} + \frac{40}{10 + R} \right)^{-1} + 0.23M \right]^{-1} + \frac{(2.0 - w)M}{1.6 + M} + w, \]

where the Reynolds number \( R = 2r_1u/v \), the Mach number \( M = u/c \), and \( w \) is a correction factor depending on the Reynolds number; \( w = 0.4(R < 2 \times 10^5) \) and \( w = 0.2(R > 2 \times 10^5) \). The relative velocity between gas and particles is \( u, c \) is the isothermal sound speed, \( v \) is the kinetic viscosity \( v = 0.353\sqrt{8\pi c\ell_g} \) (Champman & Cowling 1970), and \( \ell_g \) is the mean free path. Figure 2 shows the value of \( C_D \) as a function of the Mach number and the Reynolds number.

As in Equation (4), \( C_D \) is a function of the two non-dimensional numbers: the Mach number and the Reynolds number. However, we need the ratio of the particle size to the mean free path of molecules when we evaluate the Reynolds number. Thus we convert the result of the hydrodynamic

\[ \text{We define mean free path as } \ell_g = m_{\text{mol}}/\sigma_{\text{mol}}\rho_g, \text{ where } m_{\text{mol}} \text{ and } \sigma_{\text{mol}} \text{ are the mass and collision cross section of a molecule, whereas Champman \& Cowling (1970) defined it as } \ell_g = m_{\text{mol}}/\sqrt{2}\sigma_{\text{mol}}\rho_g, \text{ which makes apparent difference of the coefficients in the formulae of viscosity.} \]
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Figure 1. Velocity (arrows) and log density (color) of the flow around the planet on the midplane with four different nested level: \( L = 1, 4, 7, 10 \), where a difference of three in level means \( 8 \times 2^3 \) times difference in spatial scale. The lengths of the arrows are normalized by the two arrows in the right bottom of the each panel. The low density region near the origin \( (\tilde{r} \lesssim 0.005) \) mainly arises from sink treatment around the origin.

(A color version of this figure is available in the online journal.)

Figure 2. Log of gas drag coefficient \( C_D \) (Equation (4)) as a function of the Reynolds number and the Mach number.

(A color version of this figure is available in the online journal.)

simulation, which is obtained in non-dimensional form, into quantities with real dimensions. To do that, we adopt a disk model for gas temperature \( T = 280 \text{K}(a/1 \text{AU})^{-1/2} \) and gas surface density \( \Sigma_g = 1.7 \times 10^4 f_H \text{kg m}^{-2}(a/1 \text{AU})^{-3/2} \), where \( f_H \) is the scaling factor relative to that of the minimum mass disk model (Hayashi 1985). We adopt \( \sigma_{\text{mol}} = 2.0 \times 10^{-19} \text{m}^2 \) and \( m_{\text{mol}} = 3.9 \times 10^{-27} \text{kg} \). We fixed \( a = 5.2 \text{AU} \) in this paper and the fiducial value for \( f_H \) is 1.

2.3. Numerical Method

We integrate Equation (1) for particles with a wide range of size, using the Runge–Kutta–Fehlberg method with adaptive step size (e.g., Press et al. 2007). We consider a two-dimensional problem: the orbits of the particles are in the same plane of the planet orbit and the midplane of the protoplanetary disk. We also restrict ourselves to initially zero-eccentricity particles. Because of these simplification, we only have one parameter: the impact parameter \( \tilde{b} \), which is defined as the value of the \( x \) coordinate of the particle position at \( \tilde{y} \to \infty \). In the numerical simulation, we cannot set infinite \( \tilde{y} \) as an initial position of the particles, thus we set the initial position \( (\tilde{x}_0, \tilde{y}_0) \), where \( \tilde{x}_0^2 = \tilde{b}^2 - 8/\tilde{y}_0 \), which is valid when \( \tilde{x}_0 \ll \tilde{y}_0 \) (Ida & Nakazawa 1989; Ohtsuki 1999). We set \( \tilde{y}_0 = 100 \) and \( \tilde{x}_0 \) is less than 3, so the double inequalities are met in our case.
The termination conditions of the orbital integration are as follows. (1) Collision with the planet. We terminate numerical integration when \( \tilde{r} < \tilde{r}_p \), where \( \tilde{r}_p \) is the physical size of the planet in our unit. We set \( \tilde{r}_p = 0.001 \), which roughly corresponds to the physical size of a planet at 5 AU. In the gas-free case, results depend on the size of the planet, but we mainly focus on the case where particles are captured by the circumplanetary disks, not by the planet, so the physical size of the planet is not important in this work as long as the size is small enough. (2) Receding from the planet: \( |\tilde{y}| > y_0 \). These particles first approach within at least about a few Hill’s radii and then move away from the planet without collision with the planet or capture by the circumplanetary disk.

As described above, the particles are assumed to be on the midplane of the protoplanetary disk and initially in a circular orbit around the central star. We consider a wide range of particle size, so this assumption would not be always valid, but particles in a size range in which accretion to the circumplanetary disk is effective (see Section 3) can be considered to settle down toward the midplane even when we consider stirring up of particles by turbulence. The thickness of the solid particles \( h_d \) is given by (Okuzumi et al. 2012; Youdin & Lithwick 2007)

\[
h_d = h \left( 1 + \frac{\Omega_s}{\alpha} \left( \frac{1 + 2\Omega_s t_s}{1 + \Omega_s} \right) \right)^{-1/2}, \tag{5}
\]

where \( \Omega \) is angular velocity of Keplerian rotation around the central star, \( \alpha \) is non-dimensional turbulent viscous parameter (Shakura & Sunyaev 1973), \( t_s \) is stopping time of particles. If we assume \( \alpha \sim 10^{-2} \), the thickness of the 1 m sized particle layer is 1/10 of the scale height of the gas disk at 5 AU, and the typical size for effective accretion is roughly larger than 1 m, as we will see, so the two-dimensional approximation is reasonable. Once particles are in a thin layer, inclination cannot be pumped up by gravitational scattering. On the other hand, eccentricity is easier to enhance by planet gravity (Ida 1990; Ohtsuki et al. 2002). If the synodic period is longer than the stopping time, the assumption of circular orbit should be valid because eccentricity would be damped by Keplerian shear until the next approach. This condition roughly corresponds to the size \( r_s \lesssim 100 \) m. Particles with sizes larger than \( \sim 100 \) m, however, would have some eccentricity comparable to the order of unity when they approach the planet, which would affect the result. Although we should keep this in mind, we assume a circular orbit for the initial condition of the particles for simplicity.  

3. RESULTS

3.1. Typical Orbits of Captured Particles

3.1.1. Strong Gas Drag Case: Orbits of Small Particles

We first describe particle motion in the case of strong gas drag, which corresponds to particles with sizes roughly smaller than 1 m. Figure 3 shows the orbits of small particles \( r_s \lesssim 10 \) m around the Hill sphere. Figure 3(a) shows orbits of 1 cm size, which is almost the same as the streamline of gas because gas and particles are well coupled. Gas in the region \( \tilde{x} > 0 \) approaches with Keplerian shear motion in the negative \( \tilde{y} \) direction from the large \( \tilde{y} \) region. Gas that closes with the Hill sphere passes the shock surface which enhances density and reduces velocity. Gas that reaches about \( (\tilde{x}, \tilde{y}) \sim (1.0, 0.5) \) bifurcates toward two streams in front of the Hill sphere; one crosses the \( \gamma \)-axis (the planet orbit), makes a U-turn, and goes back to the positive \( \gamma \) direction. The other stream passes the Hill sphere without crossing the \( \gamma \)-axis and moves toward the negative \( \gamma \) direction (see Figure 1 and also Tanigawa et al. 2012 for detail). Since gas in the midplane does not accrete onto the circumplanetary disk, 1 cm particles do not either. For 10 cm particles (Figure 3(b)), the overall orbits outside the Hill sphere look very similar to those of the 1 cm case, but one clear difference is that there are orbits that enter the Hill sphere and accrete onto the circumplanetary disk, although gas does not enter it through the midplane. This is because, although the particles are well coupled with gas in the Keplerian timescale, the particles just after the shock surface tend to decouple with gas on a short timescale, which leads to the deviation of the orbit from gas motion. Near the bifurcation point of the gas flow and in front of the shock surface, the motion of the particles is directed toward the planet, which enables the particles to intrude into the Hill sphere against the drag of gas that is not going to enter. This feature becomes more significant for larger particles. In the case of 1 m particles (Figure 3(c)), there is a wider band in which the particles are accreting onto the circumplanetary disk. This means that the deviation of the particle motion from the gas flow is more significant, especially after the shock surface. In addition, we can see orbits that cross with each other, which does not occur in the case of smaller particles. This is one of the typical behaviors of motion for decoupled particles. In the case of particles with 10 m (Figure 3(d)), the motion outside the Hill sphere is almost free from gas drag, but if the particles go into the Hill sphere and get closer to the planet, the particles are captured by the denser gas of the circumplanetary disk at the deeper region. Note that there is an orbit that looks like it is deflected at \( (\tilde{x}, \tilde{y}) \simeq (0.2, 1.0) \), which is an apparent motion on the rotating frame. The particles are actually rotating smoothly on the inertial frame, even around the apparent deflected point, but the Hill coordinates are rotating with the Keplerian angular velocity of the planet orbital motion, and the rotating velocity is subtracted from the Hill coordinate. Thus the orbit looks deflected. This feature is notable where the distance from the planet is near the Hill radius because, in that region, the Keplerian angular velocity around the planet is close to that around the central star.

3.1.2. Weak Gas Drag Case: Orbits of Large Particles

Next, we describe particle motion in the case of weaker gas drag, which corresponds to particles with sizes larger than roughly 1 m, although the size ranges for the two cases (strong and weak gas drag) overlap with each other, which promotes a deeper understanding of the capturing processes. Before showing the orbits of the particles, we introduce a minimum distance to the planet of an orbit as a function of the impact parameter \( \tilde{b} \) in the gas free case. Figure 4 shows the minimum distance between particles from the planet through the orbits for gas-free case, which was presented by Petit & Henon (1986) and Ida & Nakazawa (1989). The distance is referred to as \( \tilde{r}_{\text{min,free}} \) in this paper. There are two main collisional bands (Giuli 1968), which divide the encounter type into three in terms of encounter direction; \( \tilde{b} \lesssim 2.1, 2.1 \lesssim \tilde{b} \lesssim 2.4, \) and \( \tilde{b} \gtrsim 2.4, \) which correspond, respectively, to prograde, retrograde, and prograde encounters. We can expect that in the retrograde encounter regime, particles tend to have strong gas drag and are easy to capture, while particles in the prograde encounter regime are more difficult to capture. Note that there are very narrow bands which show close encounter in a discontinuity manner with respect to \( \tilde{b} \), which arises from multiple encounters in each orbit (e.g., Nishida 1983; Ida & Nakazawa 1989). However, this
Figure 3. Orbits of particles with size $r_s = 10^{-2}$ m, $10^{-1}$ m, $10^0$ m, 10 m. Background colors show $\log_{10}$ of gas density, and the yellow and blue lines show the orbits of the particles. The black dots on the orbits are placed every 0.2 unit time. The white line shows the Hill sphere.

(A color version of this figure is available in the online journal.)

is so narrow that the bands do not have any significant effect on the solid accretion rate onto the circumplanetary disk in a statistical sense.

Figure 5 shows example orbits in the prograde capturing regime. We show the orbits of several particle sizes in the case with $\tilde{b} = 2.022$, in addition to the gas-free case which corresponds to the orbit of $\tilde{r}_\text{min} = 0.0250$ (see also Figure 4). Figure 5(a) shows orbits in a wide area, focusing on how particles approach the Hill sphere from heliocentric orbits. We cannot see any significant difference between the three cases until they reach the Hill sphere, including the gas-free case.

Figure 5(b) shows close-up view of Figure 5(a). We can see that a particle 10 cm in size does not enter the Hill sphere and recedes from it. This is because the particle is well coupled with gas, as mentioned before. The 1 m sized particle can penetrate into the Hill sphere through the low velocity gas at the post shock region. Although the deviation of the orbit from the gas flow is sensible for the intruding motion, the particle is still significantly affected by the gas that rotates in the prograde direction, thus the particle also starts rotating in the same direction. Figure 5(c) shows a more close-up view of the orbits of the other three different sizes (1 m, 100 m, 10,000 m).

In the case of the 1 m particle, we can see that it gradually spirals into inner region. In the case of the 100 m particle, the particle motion is almost the same as that of the gas-free case until the distance from the planet becomes less than about 0.2. However, after the first encounter at $(\tilde{x}, \tilde{y}) = (-0.05, 0)$, the particle is immediately circularized in a few orbits around the planet. Once the orbit is circularized, it does not change because the gas motion in this region is almost circular, which results in weak gas drag force. In the case of the 10,000 m particle, the particle moves along with the orbit of the gas-free case even around the first encounter, but the particle is captured in the Hill sphere because of energy dissipation by the gas drag through the first encounter, and the orbit becomes highly eccentric. Since the gas drag is not as effective in comparison with the smaller particle cases, it takes longer time to be circularized. In the course of the circularization, the distance of apocenter
continuously decreases, whereas the pericenter does not change significantly.

Figure 6 shows the orbits of particles in the retrograde encounter regime ($\tilde{b} = 2.174$) with several-size particles as well as the gas-free case. The distance at the closest approach for the gas-free case is $\tilde{r}_{\text{min,free}} = 0.0253$, which is similar to that of the prograde case of $\tilde{b} = 2.022$ shown above. Figure 6(a) shows orbits in the wide field. For the gas-free case, the particle enters the Hill sphere and encounters the planet, then escapes from the Hill sphere. For the small particles ($r_s = 1$ m), the motion of approaching the Hill sphere is similar to that of the gas-free case, but they cannot enter the Hill sphere because of the strong gas drag from the gas that does not enter the Hill sphere, which can also be observed in the prograde case. Figures 6(b) and (c) show close-up views of the orbits. Unlike the 1 m case, 10 m and larger particles can enter the Hill sphere across the high-density, low-velocity region after the shock surface. However, the motion of the 10 m particle is strongly affected at $\tilde{r} \lesssim 0.2$ by the motion of the gas that is in prograde rotation. Thus the 10 m particle, which was originally moving in the retrograde direction, flips direction to prograde and rotates in an almost circular orbit in accordance with the motion of the circumplanetary disk. The in-spiral motion is due to the drag from the gas, which is rotating at sub-Keplerian velocity. In the case of larger particles (100 m and 1000 m), the tendency is similar. However, the effect of the gas drag becomes weaker, so the point of turn-over to prograde becomes closer to the planet. For both cases, the particles settle into circular orbits, and the orbital radius of circularization decreases with increasing particle size. The deviation from true circles (inward spiral movement) is less significant compare to that of the 10 m case. However, in the
3.2. Capture Radius in Circumplanetary Disks

In order to consider processes of satellite formation in a circumplanetary disk, we need to know where solid particles are supplied at the circumplanetary disk. As we showed in the previous section, the captured particles eventually become circular orbits in the prograde direction in a short timescale unless the particles collide with the planet before circularization. Since the relative velocity with the gas after the circularization is very small, the timescale of orbital evolution due to gas drag becomes much longer than that for circularization. We therefore define the captured radius as the distance from the planet at circularization, which is different from the normal definition of capture in an energetic sense; Jacobi energy \( \tilde{E}_J = \tilde{v}^2/2 + \Phi \) becomes negative. More specifically, we define the captured radius at a time when either of the two condition is met: (1) circularized in the circumplanetary disk: \( \tilde{E}_J < 0, e < 0.3, \tilde{a} < 0.5, \) and \( N_w \geq 3 \), where \( e \) and \( \tilde{a} \) are eccentricity and semi-major axis of the particle around the planet, and \( N_w \) is the winding number (Kary & Dones 1996; Iwasaki & Ohtsuki 2007). When a particle crosses the \( x \)- or \( y \)-axis in the prograde direction around the planet, \( 1/4 \) is added to \( N_w \), while the same amount is subtracted from \( N_w \) when it crosses the axes in the retrograde direction. (2) Winded capture: \( \tilde{E}_J < 0 \) and \( N_w \geq 15 \). When one of the above conditions is met, the captured radius \( \tilde{r}_{\text{cap}} \) is determined as the larger of the two: pericenter of the orbit at the time when the condition is met, or the minimum distance from the planet until the time when the condition is met. We define \( \tilde{r}_{\text{cap}} \) as the larger of \( \tilde{a} \) or \( \tilde{r}_{\text{min}} \) when either of the two conditions are met, and we do not define it when neither of the two are met. The former condition (1) is mainly for the weak gas-drag cases where the orbit is gradually shifting toward circular from a highly eccentric orbit. The latter (2) is for the strong gas-drag cases where osculating Keplerian orbital elements are difficult to determine. Note that there are adjustable parameters to determine the captured radius, but the result is not sensitive to the parameters.

Figure 7 shows the captured radius as a function of \( \tilde{b} \). In the case of \( r_s = 0.1 \) m, the particles with an impact parameter between \( \tilde{b} \simeq 1.9 \) and 2.0 are captured, and particles in all of the other regimes basically do not enter the Hill sphere (see Figure 3), which is totally different behavior from the gas-free case (green dotted line). The position of the captured band is different from either of the two collision bands of the gas-free case, which reflects the fact that the motion is strongly affected case of the 10,000 m particle, the gas drag is so weak that the particle cannot change direction from retrograde to prograde in the course of the approach to the planet, and falls to the planet before circularization or change in direction in accord with gas flow.
Figure 7. Captured radius $\tilde{r}_{\text{cap}}$ (blue) and minimum distance from the planet until the particles are judged as captured by the circumplanetary disk, collision with the planet, or recede enough from the Hill sphere after encounters (red, see Section 3.2) as a function of $\tilde{b}$ for a wide range of particle size ($r_s = 0.1 \text{ m}, 1 \text{ m}, 10 \text{ m}, 100 \text{ m}, 1000 \text{ m}, 10,000 \text{ m}$). Green curves show $\tilde{r}_{\text{min,free}}$, which is the minimum distance from the planet in the gas-free case.

(A color version of this figure is available in the online journal.)

by the gas flow before approaching the Hill sphere. In the case of $r_s = 1 \text{ m}$, the captured band becomes wider in comparison with the 0.1 m case because the particles penetrate into the Hill sphere more easily through the lower-velocity higher-density region at the post shock (see Figures 1 and 3). The captured radius is smaller than that of the 0.1 m case since, to be captured by the circumplanetary disk, larger particles need a higher density of gas, and the gas density in the circumplanetary disk increases with decreasing distance from the planet.

In the cases of $r_s = 10 \text{ m}, 100 \text{ m}, 1000 \text{ m}$, they show similar behaviors with some quantitative differences. In this size regime, the particles are basically decoupled from the gas flow outside of
the Hill sphere, which is confirmed by the fact that the minimum distance from the planet outside the captured band matches well with that of the gas-free case (see the red and green lines in Figure 7). The width of the captured band decreases slightly with increasing particle size, which reflects that the effect of the gas drag on capture becomes more effective in the region closer to the planet where gas density and relative velocity are generally higher. There is a flat region at the bottom of $\tilde{r}_{\text{cap}}$ for each panel. We define the radius of the flat region as the critical radius for capture $\tilde{r}_{\text{cap, crit}}$. Once particles enter the radius, gas drag is so strong that the particles are forced to move with the gas flow of the circumplanetary disk regardless of the orbits before they reach the radius. The typical cases for this kind of capture can be seen in the retrograde encounter region (see Figure 6); all the particles in the retrograde encounter region are captured by the circumplanetary disk. However, in both edges of the captured band, we can see the captured region where $\tilde{r}_{\text{min, free}}$ is larger than the critical radius. In this region, the particle is first captured energetically (i.e., $E_I < 0$) in a highly eccentric orbit with the pericenter around $\tilde{r}_{\text{min, free}}$, and then circularized. During the circularization process, the particles tend to keep the pericenter, thus $\tilde{r}_{\text{cap}}$ is roughly aligned with $\tilde{r}_{\text{min, free}}$ in this regime.

In the cases of $r_s = 100$ m and 1000 m, there is a band where $\tilde{r}_{\text{cap}} < \tilde{r}_{\text{min, free}}$ around $\tilde{b} \sim 2.2$–2.3. The particles in this region approach the planet in the retrograde direction, and thus the particles cannot pass through near the $\tilde{r}_{\text{min, free}}$ as a pericenter and cannot make an elliptic orbit like that which occurred in the two edge regions. Instead, the particles are forced to change their direction into prograde and rotate with the disk gas which is rotating in almost Keplerian motion.

In the case of $r_s = 10\,000$ m, there is no flat and base region for $\tilde{r}_{\text{cap}}$ because the critical radius for capture is smaller than the planet physical radius, which means the particles collide with the planet. In other words, the gas drag is not strong enough to change the direction from retrograde to prograde in the course of approaching the planet.

In order to understand the capturing processes more deeply, we study particle-size dependence of the captured radius. Since the capture radius is a function of $\tilde{b}$ even for single size particles, as seen in Figure 7, we introduce a critical radius for capture $\tilde{r}_{\text{cap, crit}}$ as a typical capture radius for a given size regardless of $\tilde{b}$ so that we do not need to consider the detail of the $\tilde{b}$ dependence. We define $\tilde{r}_{\text{cap, crit}}$ by the radius where the captured radius $\tilde{r}_{\text{cap}}$ (blue dots in Figure 7) shows a wide and flat region at the bottom of $\tilde{r}_{\text{cap}}$ as seen in Figures 7 (a)–(e). In order to define $\tilde{r}_{\text{cap, crit}}$, we introduce two other radii $\tilde{r}_{\text{cap, 1/4}}$ and $\tilde{r}_{\text{cap, 1/2}}$; $\tilde{r}_{\text{cap, 1/4}}$ is defined so that the number of captured particles with $\tilde{r}_{\text{cap}} < \tilde{r}_{\text{cap, 1/4}}$ account for 1/4 of all the captured particles under the condition of a uniform interval in $\tilde{b}$, and $\tilde{r}_{\text{cap, 1/2}}$ is defined in the same way. The width of the bottom region is roughly half of the whole captured band, thus we define $\tilde{r}_{\text{cap, crit}} = \tilde{r}_{\text{cap, 1/4}}$ when $\tilde{r}_{\text{cap, 1/4}} \simeq \tilde{r}_{\text{cap, 1/2}}$. If the difference is large, for example, $\tilde{r}_{\text{cap, 1/2}}/\tilde{r}_{\text{cap, 1/4}} > 1.1$, the $\tilde{r}_{\text{cap, crit}}$ is smaller than $\tilde{r}_{\text{ps}}$, and many particles collide with the planet, as seen in Figure 7(f), and we do not define $\tilde{r}_{\text{min, crit}}$.

Figure 8 shows normalized capture radii $\tilde{r}_{\text{cap, 1/4}}$ and $\tilde{r}_{\text{cap, 1/2}}$ in the cases with three different scaling factors of the gas surface density $f_H = 10^{-2}, 10^{-4}$ (see Section 2.2.3). First, we can clearly see the tendency that both of the two radii decrease with increasing particle size, which is observed in Figure 7. We can also see that the difference between the two is small when the radii are larger than $10^{-2}$. In this regime, $\tilde{r}_{\text{cap, crit}}$ can be well defined by $\tilde{r}_{\text{cap, 1/4}}$. Note that the main reason why the difference between the two radii become large at $\tilde{r}_{\text{cap}} \lesssim 10^{-2}$ is the artificial effect of the background flow; the gas density at the midplane of the circumplanetary disk in $\tilde{r}_{\text{cap}} \lesssim 10^{-2}$ tends to be smaller because of sink treatment near the origin in the hydrodynamic simulation, in which the gas drag effect would be underestimated.

The decrease of gas density (i.e., $f_H$) basically makes the lines shift toward the left in the figure, because particles have to move deeper into the denser region to be captured when the whole gas density is uniformly smaller. Decrease of $f_H$, which corresponds to gas depletion of the protoplanetary disk due to gap formation around the planet orbit or global disk dissipation, basically makes the lines shift toward the left in the figure, because particles have to go deeper into the denser region to be captured when the whole gas density is uniformly smaller.

Note, however, that this is not a simple linear dependence because the gas drag coefficient $C_D$ is generally not a simple power-law function of the Reynolds number and the Mach number (Adachi et al. 1976), and the coefficient we use is not either (see Section 2.2.3). In particular, in the case of high surface density ($f_H = 1$), the gas drag law can be the Stokes regime where drag force is independent of gas density, which can change the tendency, and which is reflected on the jagged curve of case $f_H = 1$.

We also plot fitted lines of $\tilde{r}_{\text{cap, crit}}$ in the region where $\tilde{r}_{\text{cap}} \gtrsim 10^{-2}$ is given by

$$\tilde{r}_{\text{cap}} = 0.16 \left( \frac{r_s}{1\, \text{m}} \right)^{-0.4} \left( \frac{f_H}{1} \right)^{0.4}.$$  \hspace{1cm} (6)

Although this is an empirical formula, the value of 0.4 in the index can also be estimated by the balance between energy dissipation due to gas drag and the kinetic energy of particles assuming that $C_D$ is constant and that particle velocity is determined only by the potential energy of the planet. If we assume gas density is axisymmetric and the density is described
by a power-law function as \( P_s \propto r^{-\gamma} \), capture radius can be analytically obtained as \( \bar{r}_{\text{cap}} \propto r_s^{1/(1-\gamma)} \), which is derived by a comparison between dissipation energy through gas drag and the potential energy needed to be captured by the planet gravity (see Tanigawa & Ohtsuki 2010; Fujita et al. 2013 in detail). Equating the two indexes on \( r_s \), we have \( \gamma = 3.5 \), which is consistent with the density distribution we use (Tanigawa et al. 2012). We also show a simple mean radius with respect to \( \bar{b} \), given by

\[
\langle \bar{r}_{\text{cap}} \rangle = \exp \left( \int_0^{\infty} \frac{\log(\bar{r}_{\text{cap}})}{2} \frac{db}{d\bar{b}} \right), \quad \text{for all the captured orbits.} \tag{7}
\]

The mean radius \( \langle \bar{r}_{\text{cap}} \rangle \) also shows a similar trend of \( \bar{r}_{\text{cap},1/2} \), but since the distribution is far from symmetric about the mean value, the mean radius is not necessarily suitable to define \( \bar{r}_{\text{cap},\text{crit}} \).

### 3.3. Capture Rate by Circumplanetary Disks

Figure 9 shows the normalized probabilities of capture by the circumplanetary disk and the planet.

We define the normalized probabilities captured by the circumplanetary disk and the planet as

\[
P_{\text{disk}}(r_s, f_{\text{hit}}) = 2 \int_0^{\infty} \varphi_{\text{disk}}(r_s, f_{\text{hit}}, \bar{b}) \frac{\bar{b}}{2} d\bar{b}, \tag{8}
\]

\[
P_{\text{planet}}(r_s, f_{\text{hit}}) = 2 \int_0^{\infty} \varphi_{\text{planet}}(r_s, f_{\text{hit}}, \bar{b}) \frac{\bar{b}}{2} d\bar{b}, \tag{9}
\]

where \( \varphi_{\text{disk}} \) is a judgment function of whether a particle is captured by the circumplanetary disk: unity if the particle is captured, and zero otherwise. The definition of \( \varphi_{\text{planet}} \) is similar; unity if the particle collides with the planet, and zero otherwise. Note that all the particles that are judged as captured by the circumplanetary disk are going to collide with the planet after long term inward orbital evolution by gas drag, but we use the conditions for capture described in Section 3.2.

Although we show three different \( f_{\text{hit}} \), we do not see a significant qualitative difference between them, so we focus on the case of \( f_{\text{hit}} = 1 \) below, unless stated otherwise. In the limit of small particle size \( (r_s \leq 0.01 \text{ m}) \), both \( P_{\text{disk}} \) and \( P_{\text{planet}} \) are zero because small particles that are well coupled with gas cannot enter into the Hill sphere. From \( r_s = 0.1 \text{ m} \) to \( 10 \text{ m} \), \( P_{\text{disk}} \) increases with \( r_s \), which corresponds to the increase of the captured band seen in Figures 7(a)–(c). However, \( P_{\text{planet}} \) is still zero because all the particles that enter the Hill sphere are captured by the circumplanetary disk. From \( r_s = 10 \text{ m} \) to \( 1000 \text{ m} \), \( P_{\text{disk}} \) does not change significantly because the width of the captured band weakly decrease with \( r_s \) as described in Section 3.2. When \( r_s \geq 1000 \text{ m} \), \( P_{\text{disk}} \) decreases with increasing \( r_s \). This is because gas drag becomes ineffective and some fraction of particles collide with the planet rather than being captured by the circumplanetary disk. In the limit of \( r_s \to \infty \), we expect \( P_{\text{disk}} = 0 \) and \( P_{\text{planet}} = 11.3 \sqrt{r_s} \) (Ida & Nakazawa 1989; Inaba et al. 2001). In our setting \( (\bar{r}_p = 10^{-3}) \), we have \( P_{\text{planet}} = 0.36 \), in which \( P_{\text{planet}} \) is approaching with increasing \( r_s \). Note that the reason why \( P_{\text{planet}} > 0.36 \) in this weak-drag regime is that gas drag enhances the collision rate onto the planet (Inaba & Ikoma 2003; Tanigawa & Ohtsuki 2010).

Finally, we fit \( P_{\text{disk}} \) by a formula. An empirical formula for \( P_{\text{disk}} \) can be roughly approximated as

\[
P_{\text{disk}}(r_s, f_{\text{hit}}) = \begin{cases} 
P_{\text{max}} \exp \left[ -\left( \frac{\log(r_s/r_{s,\text{peak}})}{\log W_{\text{WHIM}}} \right)^2 \right] \quad & \text{if } r_s \geq 5 \times 10^{-4} r_{s,\text{peak}}, \\
0 \quad & \text{otherwise},
\end{cases} \tag{10}
\]

where \( P_{\text{max}} = 4.0 \), \( r_{s,\text{peak}} = 70 f_{\text{hit}} \text{ m} \), and \( W_{\text{WHIM}} = 100 \). The fitted lines are also plotted in Figure 9. This formula is not derived by physical considerations, but it might be useful for a rough estimation.

### 4. DISCUSSION

We have assumed so far that particle surface density is uniform in the protoplanetary disk before particles approach the planet, but that is not true in general. In particular, a particle gap, which is a lower surface density annular region around the planet orbit, can form more easily than the gap of gas (e.g., Tanaka & Ida 1997; Paardekooper 2007; Zhou and Lin 2007; Shiraiishi & Ida 2008; Ayliffe et al. 2012). We will examine the effect of gap opening on the accretion rate of particles. To examine the effect, we calculate \( \bar{r}_{\text{cap}} \) and \( P_{\text{disk}} \) as a function of the gap width that we define by \( \bar{b}_{\text{min}} \), so that particles uniformly exist at \( \bar{b} > \bar{b}_{\text{min}} \) and there are no particles at \( \bar{b} < \bar{b}_{\text{min}} \). Figure 10 shows the dependence of \( \bar{r}_{\text{cap},1/2} \), \( \bar{r}_{\text{cap},1/4} \), and \( \langle \bar{r}_{\text{cap}} \rangle \) on \( \bar{b}_{\text{min}} \). In the case with \( r_s = 1 \text{ m} \), \( \bar{r}_{\text{cap}} \) does not depend on \( \bar{b}_{\text{min}} \) almost at all, and even in the \( r_s = 10^2 \text{ m} \) and \( 10^6 \text{ m} \) cases, \( \bar{r}_{\text{cap}} \) changes only by a factor of a few. This shows that even when the particle gap is formed and the particle distribution is far from uniform, there is no significant impact on the capture radius.

Figure 11 shows \( P_{\text{disk}} \) as a function of \( \bar{b}_{\text{min}} \) for various values of \( r_s \). In contrast to Figure 10, we can see that \( P_{\text{disk}} \) decreases almost linearly with \( \bar{b}_{\text{min}} \) in the region where particles are captured. This can be easily understood by Figure 7. This simply means that when the particle gap opens wide, the accretion rate onto the circumplanetary disk is reduced, and when \( \bar{b}_{\text{min}} \gtrsim 2.4 \) no particle accretion is expected. Note that the horizontal parts of the lines indicate non-capture regions such as 1.93 < \( \bar{b} < 1.98 \) in Figure 7(e) or 2.09 < \( \bar{b} < 2.40 \) in Figure 7(f).
be able to approach the planet (Rice et al. 2006; Paardekooper particles in a particular size range can pass through the gap and gap and dam the radial flow of particles toward the planet, would probably change the estimation here.

density change, such as gap formation of the gas disk), which formula beyond their assumption (i.e., they do not consider large disks (see Figure 11). Note, however, that we extrapolate their instability (Chandrasekhar 1961; Papaloizou and Pringle 1984), the gas generates hydrodynamic instability such as Rayleigh instability (Klahr & Bodenheimer 2003), which generate a vortex and disturb the gas flow, which promote particle diffusion and the resultant satellite formation.

Muto & Inutsuka (2009) derived an analytic formula that describes the radial migration of small particles near a low-mass planet embedded in a protoplanetary disk. According to Equation (68) of their paper and comparing the two dominant terms (gravitational scattering by the planet and radial inward migration due to slight difference of rotation velocities), we obtain the gap width, which corresponds to \( \tilde{b}_{\text{min}} \) in this study, as 2.04, in the case where the normalized stopping time is unity and the degree of non-Keplerian rotation of disk gas (\( \eta \) in their notation) is \( 10^{-3} \). This would mean that the particle gap is still narrow enough for particles to accrete onto the circumplanetary disks (see Figure 11). Note, however, that we extrapolate their formula beyond their assumption (i.e., they do not consider large density change, such as gap formation of the gas disk), which would probably change the estimation here.

Although the gap structure of the gas would create a particle gap and dam the radial flow of particles toward the planet, particles in a particular size range can pass through the gap and be able to approach the planet (Rice et al. 2006; Paardekooper 2007; Ward 2009; Morbidelli & Nesvorny 2012; Zhu et al. 2012). Also, a strong pressure gradient at the gap edge of the gas generates hydrodynamic instability such as Rayleigh instability (Chandrasekhar 1961; Papaloizou and Pringle 1984), Rossby wave instability (Li et al. 2001; Lin 2013), and baloclinic instability (Klahr & Bodenheimer 2003), which generate a vortex and disturb the gas flow, which promote particle diffusion in the radial direction, then particles can approach to the planet. The dynamics at the gap edge with particles has not been well understood, so a detailed investigation of the gap dynamics is needed to understand solid accretion onto circumplanetary disks and the resultant satellite formation.

Recently, Fujita et al. (2013) investigated the motion of planetesimals in heliocentric orbits in order to examine whether the planetesimals are captured by the circumplanetary disk of giant planets. They focus on planetesimals with sizes larger than that of ours, which means that gas drag is weak. They assume that the circumplanetary disk is axisymmetric around the planet and hydrostatic equilibrium exists in the direction perpendicular to the disk central plane, which is justified by their setting of large size objects. Although they do not obtain the capture radius which we show in this paper, they consider non-zero initial eccentricity and inclination for the approaching objects. Fujita et al. (2013) and our work are thus in a mutually complementary relationship, and future works along the lines of these studies will provide a better understanding of satellite formation processes.

In this study, we observe that captured particles are rotating in the prograde direction, and Johansen & Lacerda (2010) also showed that particles of a few centimeters in radius are rotating in the prograde direction around protoplanets of a few hundred kilometers when the particles are captured by the protoplanets. Since particle density is much higher than gas density, particle motion seems to determine the rotating direction, whereas particles are dragged by gas that is rotating in the prograde direction in our case. Although there is a huge difference in mass for the two cases, we can observe the common physical property that objects in a rotating frame tend to rotate in the same direction as the frame rotation by the Coriolis force when they are pulled toward the center, as in tropical cyclones.

We have examined how particles in heliocentric orbits are captured by circumplanetary disks, but the captured particles, which are rotating at a velocity similar to that of the circumplanetary disk gas, are still migrating inward because of slight difference of the rotation velocities between gas and particles. This inward drift of particles in circumplanetary disks is important in the context of satellite formation because when the accretion rate of particles into the circumplanetary disks, which we have obtained, is given, the radial velocity determines the surface density of the solid, which would then determine the satellite growth rate. Assuming that the circumplanetary disk is axisymmetric and isothermal, we can obtain rotation velocity of gas, gas drag force acting on the particles, and then inward migration velocity for the particles (Weidenschilling 1977; Nakagawa et al. 1986). For example, inward velocity for 1 m particles is about 5 m s\(^{-1}\) at 0.01 Hill radius from the planet, which corresponds to \( \sim 7 R_J \) for a planet at 5 AU. Applying the accretion rate given by Equation (10) and assuming steady state inward particle flow, we can estimate solid surface density as \( 1 \text{ g cm}^{-2} \), which might be a bit small for satellite formation. However, the solid surface density estimated depends on particle size and gas density (which corresponds to \( f_{\text{hi}} \) in this paper), and the drag law itself depends on the two parameters. Thus these dependences

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**Figure 10.** Dependence of mean capture radius \( \tilde{r}_{\text{cap}} \) on width of particle gap. Horizontal axis is \( \tilde{b}_{\text{min}} \), which is the lower bound of the region where particles exist. Red, green and blue show the case with \( r_s = 1, 10^5, 10^6 \) m particles, respectively. Filled circles show log average and error bars show one sigma. Thick lines and thin dashed lines show \( \tilde{r}_{\text{cap},1/4} \) and \( \tilde{r}_{\text{cap},1/2} \), respectively.

(A color version of this figure is available in the online journal.)

**Figure 11.** Dependence of normalized probability of the capture by the circumplanetary disk on the width of the particle gap.

(A color version of this figure is available in the online journal.)

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have to be examined in the future. In addition, the size of particles in heliocentric orbits near giant planets is important for the satellite formation processes because it affects the accretion rate obtained in this study and the filtering effect for particles at the edge of gas gap produced by the giant planet. A recent statistical method that uses a coagulation equation with fragmentation showed that a large amount of particles of 1–100 m in size are produced by fragmentation (Kobayashi et al. 2012). A comprehensive circumplanetary disk model that considers the size distribution of incoming particles and growth in the disk would be necessary in the future in order to understand more realistic satellite formation processes.

Crida & Charnoz (2012) recently proposed a totally different mechanism to reproduce the regular satellites. They considered a heavy and compact ring composed of small particles. Diffusion processes in the ring make it spread outward, and once particles are transported beyond the Roche limit, they are allowed to accumulate gravitationally to be a larger clump, which is a proto-satellite. The proto-satellite moves outward through tidal interaction with the planet and the ring, and once the proto-satellite migrates far enough, the second proto-satellite starts to form. The ring produces many proto-satellites in this way. However, the tidal interactions of outer (older) satellites are weaker, they migrate slower than inner ones, and tend to be captured by inner ones, which leads to outer satellites tending to be larger. Since this “pyramidal” size distribution is consistent with the current icy satellites around Saturn, Uranus, and Neptune, this mechanism would be likely to have occurred. This scenario needs to have a heavy ring around the planet. Estrada & Mosqueira (2006) proposed a mechanism to supply solid materials into the Hill radius by collisions between heliocentric planetesimals under gas-free condition, which may help to create a ring around the planet. In addition, this mechanism cannot explain Galilean satellites. Both mechanisms, formation from a gas disk with solid and formation from a ring without gas, have their advantages and disadvantages, so we may have to consider hybrid scenarios to explain the formation process of the current satellite systems.

5. CONCLUSIONS

We have demonstrated how solid particles in heliocentric orbits are captured by a circumplanetary disk around an actively growing giant planet embedded in a protoplanetary disk by using numerical integration of particle orbits with gas drag. We found that the distance from the planet (orbital radius around the planet) when the particle is captured by the circumplanetary disk decreases with increasing particle size. The captured radius is approximated by a fitting function, see Equation (6). The main contribution to the accretion is the regime where particles encounter the planet in the retrograde direction, which corresponds to the retrograde encounter regime in $\hat{b}$ space (Figure 4). We also found that the accretion efficiency is maximum when the size is $10^2$ m in the case of the surface density of the minimum mass solar nebula and 5 AU planet. The width of the profile of the normalized capture probability with respect to size is wide even in log scale (about two orders of magnitude in size). If the size is smaller than a critical size, particles cannot accrete onto the circumplanetary disk because of strong coupling with gas, which cannot accrete through the midplane even during the active gas accretion phase. The size dependence of the accretion efficiency is approximated by Equation (10). Even when a particle gap around the planet orbit is formed, the captured radius is hardly affected by the gap, but the accretion rate would be reduced and could be zero depending on the gap width. Several studies on the formation of particle gaps have been performed. In particular, particle motion is strongly affected by the motion of gas, and the structure of the gas gap was not well understood at this stage mainly because the gas gap structure is affected by some hydrodynamic instability. The effect of the particle gap is important for satellite formation, and thus more studies on gas and particle gap should be performed in the future.

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