



Theoretical study on delivery of gas and dust particles onto the circumplanetary disk of giant planets and observational study on the color and size distributions of small asteroids

前田, 夏穂

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博士論文

**Theoretical study on delivery of gas and
dust particles onto the circumplanetary
disk of giant planets
and
observational study on the color and size
distributions of small asteroids**

(巨大惑星の周惑星円盤へのガス・ダストの供給に関する
理論的研究及び
微小小惑星のカラー・サイズ分布に関する観測的研究)

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神戸大学大学院理学研究科

Maeda, Natsuho

前田 夏穂

Abstract

In order to understand the formation and evolution of the solar system, it is necessary to understand the formation and evolution of giant planet and planetesimals (asteroids) with different compositions, such as NCs and CCs. The formation process of regular satellites around giant planets and observational estimates of the size distribution of asteroids can provide important information on these processes. In this thesis, through theoretical studies on the formation process of regular satellites around giant planets and observational estimates of the size distribution of asteroids with different compositions, we have attempted to obtain clues to the formation and evolution of the solar system. First, in order to reveal gas and dust accretion that leads to satellite formation around giant planets, we investigated gas accretion onto the circumplanetary disks (CPDs) and the source region of accreting gas. We investigated the planetary-mass dependence of radial/vertical distribution of source regions of streamlines that accrete onto the CPD. We also derived semi-analytical formulae of gas mass accretion rate onto the CPD by combining our results with the gap model previously obtained from global hydrodynamic simulations, which could improve models of giant planet formation (Chapter 2). Second, we investigated the planetary-mass dependence of dust accretion onto the CPD by orbital integration of dust particles approaching the planet, considering the gas drag force using the gas field obtained by our hydrodynamic simulation. Using the numerical results and the semi-analytical approaches, we derived the planetary-mass dependence of the degree of dust retention in accreting gas, which determines the mass fraction of solid particles in the gas accreting onto the CPD, a key parameter in satellite formation in the CPD (Chapter 3). The planetary-mass dependence of the supply of satellite materials obtained by this work is helpful to the construction of satellite formation models. Finally, we measured the size distributions of reddish and bluish asteroids using the observational data obtained by the Hyper Suprime-Cam installed on the Subaru Telescope (Chapter 4). We revealed the similarity of these two distributions in the size range from 0.4 to 5 km, suggesting a similarity in the collisional and dynamical behavior of these two asteroid populations with different compositions in this size range. The results of this work provide constraints on the physical properties and collisional evolution processes of asteroids with different compositions, providing important insights into the formation and evolution of the solar system.

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Chapter 1

Introduction

A wide variety of exoplanetary systems and protoplanetary disks (PPDs) with diverse structures have been discovered one after another, largely by the Kepler space telescope and the Atacama Large Millimeter/Sub-Millimeter Array (ALMA) (e.g., Fressin et al. 2013, Andrews et al. 2018). In this context, the question of how our solar system formed and evolved is even more important for understanding the planet formation process. Based on isotope measurements of meteorites, primitive meteorites can be roughly classified into two groups: non-carbonaceous (NC), such as ordinary chondrites, and carbonaceous (CC), such as carbonaceous chondrites (Warren 2011). Further detailed analysis has revealed that NCs and CCs likely formed two distinct reservoirs that coexisted and remained spatially separated for several Myr in the early solar nebula. The spatial separation of the reservoirs was likely caused by some processes, and one possibility is the gaps and rings in the solar nebula due to the formation of giant planets (Kruijer et al. 2017). Integrated studies of the growth and orbital migration of giant planets and the associated orbital evolution of planetesimals showed that implantation from the formation sites of CCs to their current positions depend on the timing and location of the formation of Jupiter and Saturn (Raymond & Izidoro 2017). Thus, the formation and evolution processes of planetesimals with different compositions, such as NCs and CCs, are important issues in understanding the formation and evolution of the solar system, and the formation of giant planets is key to this process. This thesis focus on the formation of regular satellites, a byproduct of the formation of giant planets (Chapters 2 and 3). Also, in order to obtain constraints on the formation and evolution processes of NCs and CCs, we obtain observational constraints on their dynamical behavior (Chapter 4).

Giant planets such as Jupiter and Saturn accumulate the gas from the PPD due to their gravity during their formation. First, the gas captured by the planet forms a spherical envelope around the solid core, and the so-called runaway gas accretion begins when the core mass exceeds a critical value and the atmosphere becomes too massive to maintain hydrostatic equilibrium (e.g., Pollack et al. 1996). Then, the circumplanetary disk (CPD), a gaseous disk around the planet, is formed due to the angular momentum of the gas when the planet becomes sufficiently massive (e.g., Lubow et al. 1999). Recently, some CPD candidates have been detected around exoplanets by observations of PPDs (e.g., Isella et al. 2019). Protoplanets accrete the gas and solid particles via the CPD, and satellites are formed by the accumulation of solid particles in the CPD, similarity to the planet formation in PPDs. Regular satellites (having a prograde orbit with a very small eccentricity and inclination), such as Galilean satellites and Titan, are thought to be formed in the CPD as a byproduct of

the formation of their host planet. Understanding the gas accretion onto CPDs is important for both planet and satellite formation, because it is closely related to the accretion of solid particles, building blocks of satellites. For example, if a sufficient amount of solids can be supplied to the CPD, the cycle of accretion of satellites and their migration to the planet would have repeated multiple times (e.g., Canup & Ward 2006), but many generations of satellites may have not been able to form if the supply of solids was limited.

Recent hydrodynamical simulations show that the gas vertically accrete onto the CPD. Only the gas with a certain altitude in the PPD can accrete onto the CPD, and some of the gas accreted around the planet flows out of the Hill sphere of the planet from the midplane (Tanigawa et al. 2012, Ayliffe & Bate 2012). The dust particles settled down to the midplane in the PPD cannot accrete to the CPD due to the outflow of the gas in the midplane (Tanigawa et al. 2014). On the other hand, dust particles stirred up above the midplane can accrete to the CPD with the help of the accreting gas flow (Homma et al. 2020, Szulágyi et al. 2022). Thus, the gas flow around the planet is important to understand the dust supply onto the CPD, but the planetary-mass dependence of these processes has not been investigated in detail so far. Giant planets can grow by accumulation of solid materials during satellite formation. Thus, planetary-mass dependence of gas and dust supply onto the CPD is important to understand the time evolution of satellite formation in a certain system and also to clarify the difference in satellite formation around giant planets with various masses, such as Jupiter, Saturn, or exoplanets.

In this thesis, we performed local three-dimensional hydrodynamic simulations around planets with various masses (Chapter 2). Next, we perform orbital integration of solid particles approaching the planet, taking account of the gas drag force using the obtained gas field. Recent studies showed that one of the key parameters in satellite formation in the CPD is the ratio of dust-to-gas accretion rates, i.e., the mass fraction of solid particles in the gas accreting onto the CPD (e.g., Shibaike et al. 2017). Thus, combining the semi-analytical and numerical approaches, we derive the planetary-mass dependence of the degree of dust retention of accreting gas, which determines the ratio of dust-to-gas accretion rates (Chapter 3).

On the other hand, asteroids are thought to be planetesimal survivors that experienced collisional evolution. In particular, those that have not differentiated internally are called primitive asteroids and are likely to have preserved conditions similar to those during the formation of the solar system. Asteroids are classified according to the shape of their reflectance spectrum, and the most major types are S-type and C-type. The sample-return missions by the spacecraft Hayabusa and Hayabusa2 revealed that S-type and C-type asteroids are parent bodies of ordinary chondrites (NC) and carbonaceous chondrites (CC), respectively (Nakamura et al. 2011, Yokoyama et al. 2023). Spectroscopic studies based on ground-based observations of asteroids show that NCs, such as S-type asteroids, and CCs, such as C-type asteroids, are spatially overlapped in their radial distribution in the solar system, suggesting that there has been dynamical mixing after their formation (e.g., DeMeo & Carry 2014). Such mixing is likely caused by gravitational scattering by giant planets (e.g., Tsiganis et al. 2005). Numerical simulations of the scattering and mixing processes of planetesimals driven by giant planet growth and orbital migration show that most of C-type asteroids scattered by the growth of Jupiter and Saturn are implanted in the outer region of the main asteroid belt (Raymond & Izidoro 2017). They showed the origin of C-type asteroids is around the orbits of Jupiter and Saturn, and its implantation depends on the tim-

ing and location of the formation of Jupiter and Saturn. Also, asteroids have experienced significant collisional evolution after their accretion (e.g., Bottke et al. 2005a,b). Thus, it is important to understand the differences in the dynamical behavior of asteroids with different spectral types.

The size distribution of asteroid populations can be used to clarify their collisional evolution (e.g., Bottke et al. 2015 for a review). Comparison of size distributions of S-type and C-type asteroids may help understand the difference in their physical properties and collisional evolution. While some observational studies of the size distribution of S-/C-type asteroids have been performed (Ivezić et al. 2001, Yoshida & Nakamura 2007, Ryan et al. 2015), the sample number and the accuracy of color measurement and classification are not sufficient, and their similarity/difference has not been settled. In this thesis, we analyzed over 3,000 small main-belt asteroids using the observational data obtained by the Hyper Suprime-Cam (HSC), a wide field camera installed on the 8.2 m Subaru Telescope. We measured the size distributions of S-like/C-like asteroids using large homogenous statistical samples and discuss implications on their physical properties and collisional evolution (Chapter 4).

Finally, in Chapter 5, we will summarize this thesis in the context of the formation and evolution of the solar system, and also discuss future prospects.

Chapter 2

Delivery of Gas onto the Circumplanetary Disk of Giant Planets: Planetary-mass Dependence of the Source Region of Accreting Gas and Mass Accretion Rate ^{*1}

2.1 Introduction

Recent developments of numerical hydrodynamic simulations have made progress in understanding gas flow around protoplanets. When a protoplanet accretes gas from the protoplanetary disk (PPD), a circumplanetary disk (CPD) naturally forms around a sufficiently massive protoplanet while a spherically symmetric envelope forms around a small protoplanet (e.g., Tanigawa & Watanabe 2002, Machida et al. 2008, Machida 2009, Ayliffe & Bate 2009, Tanigawa et al. 2012, Gressel et al. 2013, Szulágyi et al. 2014, 2016, 2017, Fung et al. 2019, Lambrechts et al. 2019, Schulik et al. 2019, 2020). Whether envelopes or CPDs form depends not only on the planetary mass but also on the surface temperature of the planet and the equation of state (Szulágyi et al. 2016, 2017, Fung et al. 2019). High-resolution three-dimensional hydrodynamic simulations demonstrate a meridional circulation of the gas near a gap opened by a giant planet in the PPD: gas flows into the gap at a high altitude over the CPD, and the planet pushes the gas back into the PPD while accreting part of the gas (Tanigawa et al. 2012, Szulágyi et al. 2014, Morbidelli et al. 2014, Fung & Chiang 2016). Similar circulating flows have also been reported in simulations around less massive planets corresponding to super-Earths and sub-Neptunes (Ormel et al. 2015, Fung et al. 2015, Carbognani 2017, Kurokawa & Tanigawa 2018, Kuwahara et al. 2019).

Growing giant planets accumulate gas and solid particles via their CPD, and principal regular satellites, such as the Galilean satellites and Titan, are thought to be formed in the CPD. Thus, accretion of gas and solid particles onto the CPD is important for both planet

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and satellite formation. Kilometer-sized or larger planetesimals can be captured by gas drag from the CPD (Fujita et al. 2013). Some of the captured planetesimals can be ablated and become particles with the size of pebbles or dust, and the remaining part can become satellitesimals (Ronnet & Johansen 2020). However, capture efficiency of planetesimals significantly decreases when a gap in the planetesimal disk forms at the planet’s orbit and/or the velocity dispersion of the planetesimals is too large (Fujita et al. 2013, Suetsugu et al. 2016, Suetsugu & Ohtsuki 2017), unless the planetesimal reservoir exterior to the gap is perturbed by other planetary embryos (Ronnet et al. 2018). On the other hand, dust particles accreted with gas are also potential building blocks of satellites and would become a major contributor in circumstances where planetesimal capture is inefficient (Canup & Ward 2002, 2006, Suetsugu & Ohtsuki 2017, Shibaike et al. 2019, Batygin & Morbidelli 2020).

The motion of sufficiently small particles delivered from the PPD into the CPD is strongly influenced by the gas flow around the planet, such as the meridional circulation mentioned above. For example, using high-resolution local three-dimensional hydrodynamic simulations assuming isothermal and inviscid gas around a growing giant planet, Tanigawa et al. (2012) found that the gas vertically accretes onto the CPD but flows radially outward in the midplane, while the direction of the radial flow in the midplane of the CPD would depend on the viscosity of the gas (Szulágyi et al. 2014). Using orbital integration of particles that takes account of the gas flow obtained by Tanigawa et al. (2012), Tanigawa et al. (2014) examined accretion of particles initially confined within the midplane of the PPD. They found that mm-sized or smaller particles (i.e., those with the Stokes number significantly smaller than unity) cannot accrete into the CPD because of the strong influence of the out-flowing gas in the midplane. On the other hand, Homma et al. (2020) performed similar calculations but took account of the vertical motions of the gas and particles. They found that sufficiently small particles coupled to the vertically accreting gas can accrete onto the CPD when they are vertically stirred up in the PPD. However, they also found that the dust-to-gas ratio in the gas accreting onto the CPD can become significantly smaller than that in the PPD if the turbulence in the PPD is weak (corresponding to the turbulence parameter $\alpha \sim 10^{-4}$, Shakura & Sunyaev 1973). More recently, Bi et al. (2021) and Szulágyi et al. (2022) carried out global three-dimensional hydrodynamic simulations with dust particles. They found that the dust particles are stirred up vertically well above the midplane due to the meridional circulation, where the spiral wakes created by the planet bring up the dust from the midplane.

Thus, it is crucial for understanding satellite formation around gas giants to study the delivery of gas and dust particles onto the CPD from the PPD using three-dimensional high-resolution hydrodynamic simulations, such as the one shown in Tanigawa et al. (2012). However, Tanigawa et al. (2012) (and also Tanigawa et al. 2014 and Homma et al. 2020) examined only the case of $r_H/h_g = 1$, where r_H is the planet’s Hill radius and h_g is the scale height of the gas in the PPD, corresponding to a planetary-mass of $0.4M_{\text{Jup}}$ at the current Jovian orbit for the minimum-mass solar nebula model (MMSN; Hayashi 1981). Since formation of principal regular satellites is likely to occur during planet formation, it is necessary to understand how the flow pattern and amount of gas and dust particles delivered onto the CPD depend on planetary mass. The dependence of gas and dust supply on planetary mass will also help us understand satellite formation in different planet systems, such as Jupiter and Saturn, or exoplanet systems.

In Chapters 2 and 3, we will investigate planetary-mass dependence of delivery of gas

and dust particles onto CPDs. As the first step of understanding planetary-mass dependence of dust supply onto CPDs, we focus on gas accreting onto CPDs in this chapter. Accretion of dust particles that are not completely coupled to the gas will be investigated in Chapter 3. Details of the structure of the CPD depend not only on the planetary mass but also on various other factors such as the equation of state, viscosity, and surface temperature of the planet (Machida 2009, Machida et al. 2010, Szulágyi et al. 2014, 2016, 2017, Gressel et al. 2013, Fung et al. 2019). In contrast, the picture that the gas around a sufficiently massive planet vertically accretes onto the CPD is rather insensitive to numerical settings (Machida et al. 2010, Szulágyi et al. 2014, 2017, Gressel et al. 2013). Thus, we consider the simplest case of an isothermal and inviscid fluid, following Tanigawa et al. (2012). We perform three-dimensional high-resolution hydrodynamic simulations with various planetary masses and investigate the dependence of gas accretion on planetary mass.

The structure of this chapter is as follows. In § 2.2, we will explain basic equations and numerical settings. In § 2.3, we will show the results of hydrodynamic simulations. In § 2.4, we will derive the semi-analytical formulae of mass accretion rate of gas by combining our results with the gap model obtained from global hydrodynamic simulations (Kanagawa et al. 2015). We will also discuss comparisons with previous works in § 2.4. We will summarize this work in § 2.5.

2.2 Methods

2.2.1 Basic equations

The model used in this work is similar to those described in Machida et al. (2008) and Tanigawa et al. (2012). We consider a giant planet on a circular orbit embedded in a PPD. We erect a rotating local Cartesian coordinate system with origin at the planet, the x -axis pointing radially outward, the y -axis in the direction of the planet's orbital motion, and the z -axis in the vertical direction to the PPD midplane. We define r and R as $r \equiv \sqrt{x^2 + y^2 + z^2}$ and $R \equiv \sqrt{x^2 + y^2}$, respectively.

As in Tanigawa et al. (2012), we assume that the gas is inviscid and isothermal, and denote its density, velocity, and pressure as ρ , $\mathbf{v}$, and P , respectively. We normalize time by the inverse of the Keplerian angular velocity $\Omega_K^{-1} = (GM_c/a^3)^{-1/2}$, length by the scale height of the PPD h_g , and density by Σ_0/h_g , where G , M_c , a , and Σ_0 are the gravitational constant, mass of the central star, semi-major axis of the planet, and unperturbed surface density of the PPD, respectively. In this case, velocity is normalized by sound speed $c_s = h_g\Omega_K$. In the following, hats denote normalized quantities. Then, the basic equations can be written as (for details, see Machida et al. 2008)

$$\frac{\partial \hat{\rho}}{\partial \hat{t}} + \hat{\nabla} \cdot (\hat{\rho} \hat{\mathbf{v}}) = 0, \quad (2.1)$$

$$\frac{\partial \hat{\mathbf{v}}}{\partial \hat{t}} + (\hat{\mathbf{v}} \cdot \hat{\nabla}) \hat{\mathbf{v}} = -\frac{1}{\hat{\rho}} \hat{\nabla} \hat{P} - \hat{\nabla} \hat{\Phi} - 2\mathbf{e}_z \times \hat{\mathbf{v}}, \quad (2.2)$$

$$\hat{P} = \hat{\rho}, \quad (2.3)$$

where $\mathbf{e}_z = (0, 0, 1)$ is the unit vector in the z -direction, and

$$\hat{\Phi} = \hat{\Phi}_{\text{tidal}} + \hat{\Phi}_p + \frac{9}{2} \hat{r}_H^2, \quad (2.4)$$

$$\hat{\Phi}_{\text{tidal}} = -\frac{3}{2} \hat{x}^2 + \frac{1}{2} \hat{z}^2, \quad (2.5)$$

$$\hat{\Phi}_p = -\frac{3\hat{r}_H^3}{\hat{r}}. \quad (2.6)$$

In the above, $\hat{\Phi}_{\text{tidal}}$ is the tidal potential of the central star, $\hat{\Phi}_p$ is the gravitational potential of the planet, and a constant $(9/2)\hat{r}_H^2$ is added in Equation (2.4) so that $\hat{\Phi} = 0$ at the two Lagrangian points L_1 and L_2 of the planet; $\hat{r}_H$ is the normalized Hill radius of the planet denoted by

$$\hat{r}_H = \frac{r_H}{h_g} = \left(\frac{M_p}{3M_c} \right)^{1/3} \frac{a}{h_g}, \quad (2.7)$$

where M_p is the mass of the planet. This parameter $\hat{r}_H$ is the only one physical parameter in our formalization. Note that $\hat{r}_H = 1$ corresponds to the planetary mass M_p equal to the so-called thermal mass, $3(h_g/a)^3 M_c$ (e.g., Ginzburg & Chiang 2019)

To determine the quantitative relationship between $\hat{r}_H$ and M_p , we need to give a semi-major axis dependence of the disk scale height. If we consider an optically thin disk and assume that the temperature distribution is $T = 280 \text{ K } (a/1 \text{ au})^{-1/2}$ (Hayashi 1981), the

scale height can be derived as

$$h_g = c_s \Omega_K^{-1} = 4.93 \times 10^9 \left(\frac{a}{1 \text{ au}} \right)^{5/4} \text{ m.} \quad (2.8)$$

Using Equations (2.7) and (2.8), we obtain

$$\frac{M_p}{M_{\text{Jup}}} = 0.41 \left(\frac{M_c}{1 M_\odot} \right)^{1/2} \left(\frac{a}{5.2 \text{ au}} \right)^{3/4} \hat{r}_H^3. \quad (2.9)$$

On the other hand, recent MHD simulations show that the temperature in magnetically accreting disks is lower than that in viscous accretion disks (Mori et al. 2019). If we consider a colder disk and assume that the temperature distribution is $T = 100 \text{ K } (a/1 \text{ au})^{-3/7}$ (Kusaka et al. 1970), the scale height can be derived as

$$h_g = c_s \Omega_K^{-1} = 2.93 \times 10^9 \left(\frac{a}{1 \text{ au}} \right)^{9/7} \text{ m,} \quad (2.10)$$

and from Equations (2.7) and (2.10), we obtain

$$\frac{M_p}{M_{\text{Jup}}} = 0.098 \left(\frac{M_c}{1 M_\odot} \right)^{3/7} \left(\frac{a}{5.2 \text{ au}} \right)^{6/7} \hat{r}_H^3. \quad (2.11)$$

Figure 2.1 shows the relationship between $\hat{r}_H$ and M_p (i.e., Equations (2.9) and (2.11)) in the case of $a = 5.2 \text{ au}$ and $a = 9.6 \text{ au}$, respectively, for the two disk models described above. To investigate the dependence of gas accretion on planetary mass, we ran 11 simulations varying the value of $\hat{r}_H$ and analyzed quasi-steady state for each run. We ran the simulations with 11 values of $\hat{r}_H$ in the range of $\hat{r}_H = 0.5 - 1.36$, corresponding to $M_p = 0.05 M_{\text{Jup}} - 1 M_{\text{Jup}}$ for the Hayashi disk (Equation (2.9)) and $M_p = 0.01 M_{\text{Jup}} - 0.2 M_{\text{Jup}}$ for the cold disk (Equation (2.11)) at the current Jovian orbit, respectively.

In the following, when we refer to M_p assumed in each simulation, it is obtained from Equation (2.9) assuming $a = 5.2 \text{ au}$ (the current Jovian orbit) and $M_c = M_\odot$ (the solar mass), unless explicitly stated otherwise.

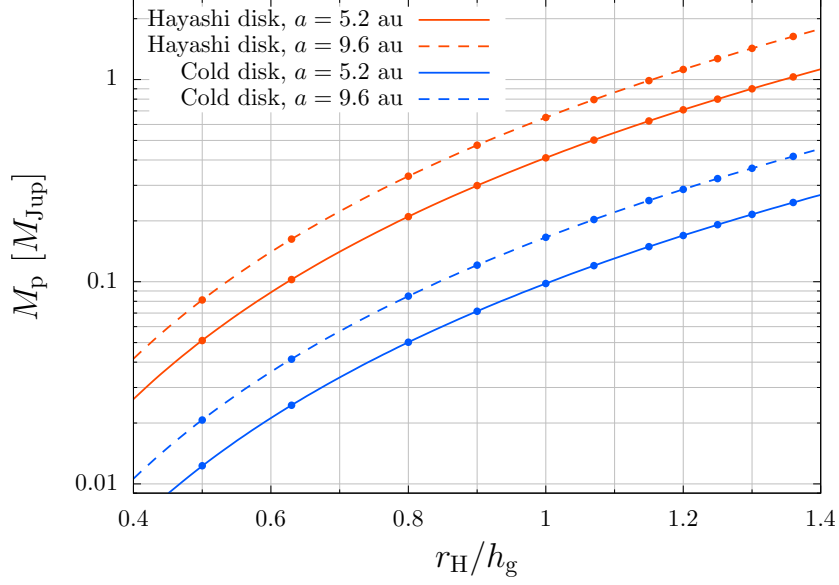


Figure 2.1: Relationship between $\hat{r}_H = r_H/h_g$ and M_p . The red lines are drawn from Equation (2.9), which corresponds to the Hayashi model ($T = 280 \text{ K } (a/1 \text{ au})^{-1/2}$). The blue lines are drawn from Equation (2.11), which corresponds to the cold disk (Kusaka) model ($T = 100 \text{ K } (a/1 \text{ au})^{-3/7}$). The solid and dashed lines show the cases for $a = 5.2 \text{ au}$ (the Jovian orbit) and 9.6 au (the Saturnian orbit), respectively. The symbols correspond to the values of $\hat{r}_H$ we adopted in our simulations.

2.2.2 Numerical settings

We used a three-dimensional nested-grid hydrodynamic simulation code (e.g., Machida et al. 2005, 2006). Our numerical settings are basically the same as in Tanigawa et al. (2012). Assuming symmetry about the $\hat{z} = 0$ plane, we set the sizes of the computational domain to $\hat{x} \in [-12, 12]$, $\hat{y} \in [-12, 12]$, and $\hat{z} \in [0, 6]$, i.e., the length of each side of the simulation box is $(\hat{L}_x, \hat{L}_y, \hat{L}_z) = (24, 24, 6)$. We set the nested-grid composed of 11 levels at maximum ($l_{\max} = 11$), where l is the level of the nested-grid. As the level increases, the length of each side is halved keeping the planet at the origin, while the numbers of cells in each grid are kept constant as $(n_x, n_y, n_z) = (64, 64, 16)$. The finest cell width is $\hat{L}_x/64/2^{11-1} = 3.66 \times 10^{-4}$, which roughly corresponds to one-fourth of the physical size of a planet with a mean density of 1 g cm^{-3} .

Initial and boundary conditions are also the same as in Tanigawa et al. (2012). Initially, the gas density distribution is in hydrostatic equilibrium in the z -direction, and the Keplerian velocity field is assumed. We set the unperturbed boundary in the x -direction, the mixed condition of unperturbed and periodic boundaries in the y -direction, and the mirror condition in the z -direction, respectively (for details, see Tanigawa et al. 2012). We set the smoothing length $r_{\text{sm}} = 2.44 \times 10^{-4} h_g$ to avoid singularity of the planet gravity, but no sink cells are set in the present work.

We set $l = 1$ at the start of each simulation and add deeper levels of grids ($l > 1$) gradually with time. We empirically determined to create a new level with $l = 2$ at $\hat{t} = 20$, $l = 3$ at $\hat{t} = 50$, and $l = 4$ at $\hat{t} = 150$, respectively, and deeper levels with $l \geq 5$ are created when the gas flow in each level is sufficiently relaxed (see also Tanigawa et al. 2012). We observed that non-negligible oscillations appeared in the density and velocity fields for the case of $\hat{r}_H > 1.0$ (i.e., $M_p > 0.4 M_{\text{Jup}}$), while quasi-stationary flow patterns can be obtained for $\hat{r}_H \leq 1.0$. In order to analyze the field data, while we use snapshots at the end of each simulation for the case of $\hat{r}_H \leq 1.0$, we obtain time-averaged values of the density and velocity for $\hat{r}_H > 1.0$ as described below. For $l \leq 4$, we take a time average for $\hat{t} \geq 150$ because numerical oscillations mainly occur in the region of $l \leq 4$. We can reduce the effect of numerical oscillation by taking a time average of the snapshots over a sufficiently long duration compared to the period of the oscillation. For $l \geq 5$, we use snapshots at the end of each simulation ($\hat{t} \sim 170$). The spatial region corresponding to $l \geq 5$ is roughly within the Hill sphere and the gas distribution is nearly axisymmetric, thus discontinuity in the gas distribution and flow patterns between this region and the other region with $l \leq 4$ is negligible. Thus, we combine time-averaging data for $l \leq 4$ and snapshots for $l \geq 5$. We confirmed that the discontinuities of combined gas fields do not significantly affect our qualitative results, while this method might affect quantitative results to some degree, such as gas accretion rates (Fung et al. 2019).

2.3 Results

2.3.1 Overview of gas fields

Figures 2.2a and 2.2b show density distributions and velocity vectors for levels $l = 1$ and 4, respectively, for the model with $\hat{r}_H = 1.36$ ($M_p = 1 M_{\text{Jup}}$) at $\hat{t} = 170$. The upper and lower panels show the distributions for the planes where the cell closest to $z = 0$ and

$y = 0$, respectively. In panel (a), two arm-like structures are extended from the planet's Hill sphere, and a gap region with low gas surface density is formed around the planet's orbit. The enlarged maps around the Hill spheres are shown in panel (b), where a CPD with high density and an axisymmetric structure can be confirmed within the Hill sphere. The vertical inflow from high altitude to the CPD along the z -axis and a weak outflow at the midplane can be observed in the lower panels.

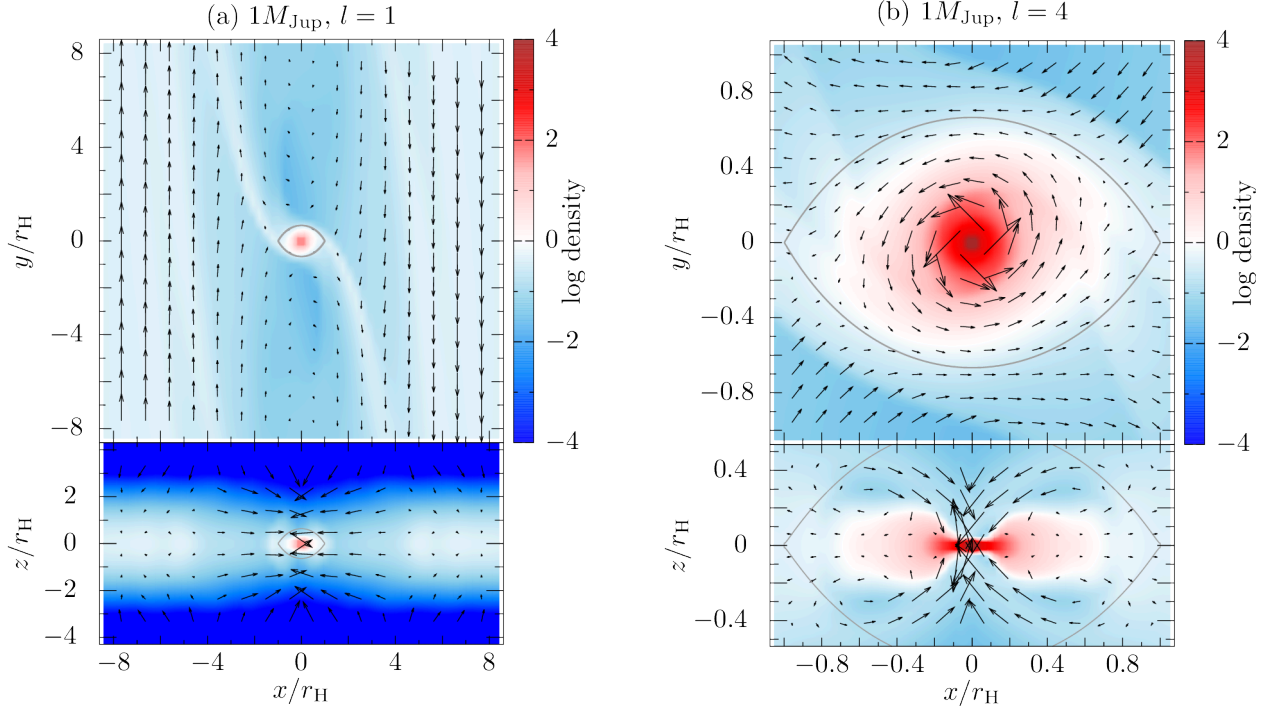


Figure 2.2: Density distributions (color) and velocity vectors (arrows) around the planet ((a) for $l = 1$, (b) for $l = 4$) for $\hat{r}_H = 1.36$ ($M_p = 1M_{\text{Jup}}$). The upper and lower panels correspond to the planes where the cell closest to $z = 0$ and $y = 0$, respectively. The lemon-shaped region enclosed by the gray line in each panel is the planet's Hill sphere (its surface is defined by $\hat{\Phi} = 0$ in Equation (2.4)). Sizes of velocity vectors are appropriately chosen in each panel.

2.3.2 Structure of gas flow within the Hill sphere

Figure 2.3 shows the radial distribution of the azimuthally averaged gas density at the midplane for the cases of $\hat{r}_H = 0.63$ ($M_p = 0.1M_{\text{Jup}}$), 1.0 ($M_p = 0.4M_{\text{Jup}}$), and 1.36 ($M_p = 1M_{\text{Jup}}$). We found that the density distributions within the Hill sphere approximately follow the power-law distribution of $\hat{\rho} \propto \hat{R}^{-3}$ for all cases, which is consistent with Tanigawa et al. (2012).

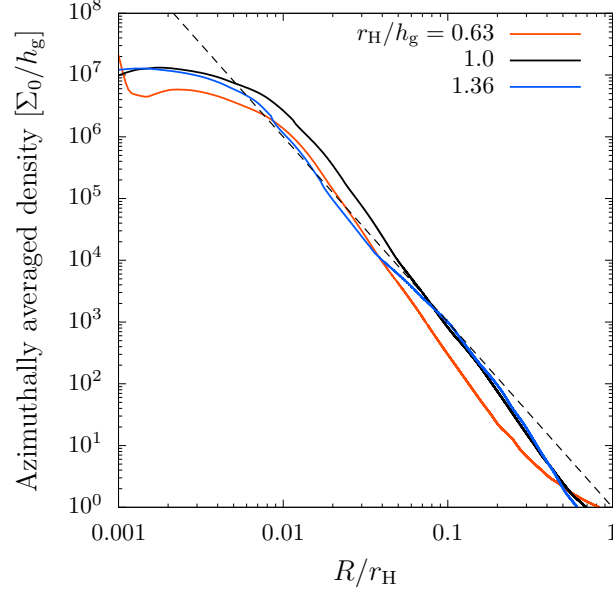


Figure 2.3: Radial density distributions at the midplane as a function of the horizontal distance from the planet $R = \sqrt{x^2 + y^2}$ scaled by the Hill radius r_H . Density is azimuthally averaged around the planet. The red, black, and blue lines correspond to the cases of $\hat{r}_H = 0.63$ ($M_p = 0.1M_{\text{Jup}}$), 1.0 ($M_p = 0.4M_{\text{Jup}}$), and 1.36 ($M_p = 1M_{\text{Jup}}$), respectively. The dashed line shows the slope for the power-law distribution of $\hat{\rho} \propto \hat{R}^{-3}$.

When the planetary mass is high enough, radial structure of the gas flow within the Hill radius is characterized by the Hill radius. Figure 2.4 shows radial distributions of radial velocity v_R (top) and the z -component of specific angular momentum j_z (bottom) around the planet at the midplane for the high mass cases ($\hat{r}_H = 1.0 - 1.36$; $M_p = 0.4M_{\text{Jup}} - 1M_{\text{Jup}}$).^{*1} Both radial velocity and specific angular momentum are azimuthally averaged around the planet and normalized by the values for the Keplerian rotation around the planet ($v_{\text{Kep,p}}$ and $j_{\text{Kep,p}}$, respectively). Note that the specific angular momentum is measured in the rotational frame. We found that the radial distributions of the scaled radial velocity and the scaled specific angular momentum do not depend on planetary mass appreciably. We also found that gas elements at $R < 0.2r_H$ (left side of the vertical dashed line) rotate with a velocity over 80% of the Keplerian velocity around the planet. Defining this region as a CPD, the radius of the CPD is $0.2r_H$, i.e., proportional to the Hill radius of the planet for $\hat{r}_H \geq 1.0$ ($M_p \geq 0.4M_{\text{Jup}}$). The CPD radius of our result is roughly consistent with previous works which examined cases for $M_p \sim M_{\text{Jup}}$ (D’Angelo et al. 2003, Ayliffe & Bate 2009, 2012, Tanigawa et al. 2012, Szulágyi et al. 2014).

For the low mass cases, on the other hand, radial structure of the gas flow within the Hill radius is characterized by the Bondi radius $r_B = GM_p/c_s^2$. Figure 2.5 shows radial distributions of v_R and j_z for the low mass cases ($\hat{r}_H = 0.5 - 0.8$; $M_p = 0.05M_{\text{Jup}} - 0.2M_{\text{Jup}}$). We found that v_R and j_z shown as a function of the horizontal radial distance scaled by the Bondi radius do not depend on planetary mass appreciably. Gas elements at $R < 0.07r_B$ (left side of the vertical dashed line) rotate with a velocity over 80% of the Keplerian velocity around the planet. Thus, the radius of the CPD in this case is proportional to the Bondi radius for $\hat{r}_H \leq 0.8$ ($M_p \leq 0.2M_{\text{Jup}}$).

Our results that the radii of CPDs are proportional to the Bondi/Hill radius in the low-/high-mass regimes are consistent with the results for the isothermal and inviscid cases in Fung et al. (2019). The transition planetary mass between the two regimes we found is roughly consistent with the expectation of Fung et al. (2019) ($\hat{r}_H \simeq 0.7$; $q_{\text{thermal}} \simeq 4$ in their notation).

^{*1}In Figure 7 of Tanigawa et al. (2012), v_R has positive values for $R < 0.006h_g$, while our result for $\hat{r}_H = 1.0$ has very small negative values for the same region. This discrepancy is caused by the difference of extrapolation methods. Extrapolation is needed to obtain the values at the midplane because physical quantities are calculated only for the $z > 0$ regions in the hydrodynamic simulation. Tanigawa et al. (2012) used quadratic functions for the extrapolation in z -direction. Although the raw values of v_R at the cells closest to the midplane are small negative values, non-negligible positive values can be artificially obtained when the points used for the extrapolation cross a discontinuity where higher-order extrapolations are not suitable, such as a surface of CPD.

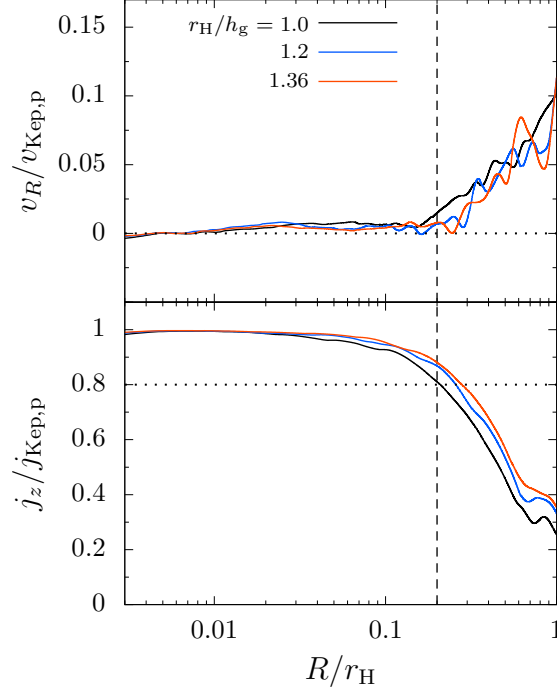


Figure 2.4: Azimuthally averaged radial velocity (top) and specific angular momentum (bottom) around the planet at the midplane, normalized by the value for the Keplerian rotation around the planet. The black, blue, and red lines correspond to the cases of $\hat{r}_H = 1.0$ ($M_p = 0.4M_{\text{Jup}}$), 1.2 ($M_p = 0.7M_{\text{Jup}}$), and 1.36 ($M_p = 1M_{\text{Jup}}$), respectively. The vertical dashed line represents the radius of the CPD, $R = 0.2r_H$. Rotational velocity of the gas at $R < 0.2r_H$ are faster than 80% of the Keplerian velocity for all cases.

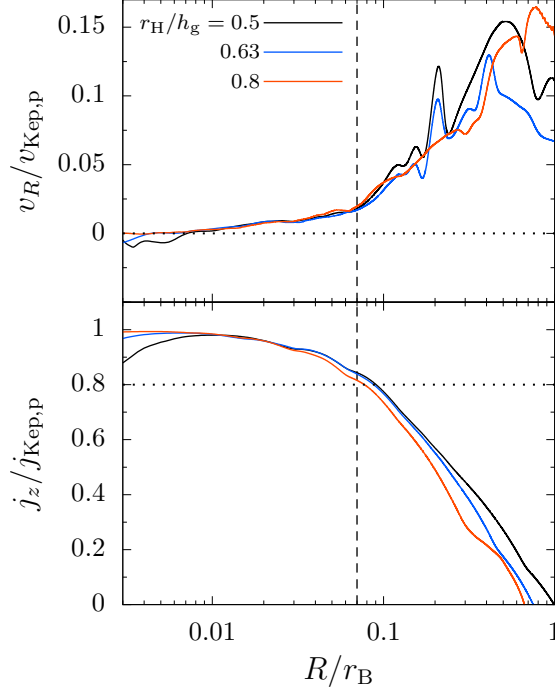


Figure 2.5: Same as Figure 2.4 but for the low planetary-mass case. The horizontal axis is normalized by the Bondi radius r_B . The black, blue, and red lines correspond to the cases of $\hat{r}_H = 0.5$ ($M_p = 0.05M_{\text{Jup}}$), 0.63 ($M_p = 0.1M_{\text{Jup}}$), and 0.8 ($M_p = 0.2M_{\text{Jup}}$), respectively. The vertical dashed line represents the radius of the CPD, $R = 0.07r_B$. Rotational velocity of the gas at $R < 0.07r_B$ is faster than 80% of the Keplerian velocity for all cases.

2.3.3 Gas accretion onto circumplanetary disks

Accretion of small particles onto a CPD is largely influenced by the flow pattern of the gas around the planet. Previous studies show that the gas coming from a limited range of radial and vertical region in the PPD can accrete onto the CPD (e.g., Tanigawa et al. 2012; we call this region "accretion band", hereafter). The initial radial location of dust particles accreting onto a CPD is related to gas accretion band (Homma et al. 2020). In this section, we focus on the radial and vertical structure of the gas accretion band, which is important for accretion of gas and dust particles into the CPD. Note that the structure of the gas accretion band is hardly influenced by the gap depth, which we cannot precisely evaluate by our local simulation.

In Figures 2.6 and 2.7, starting radial and vertical positions of streamlines (x_0 and z_0 , respectively) at $\hat{y} = 12$ are classified by color according to their final destination (Tanigawa et al. 2012, Homma et al. 2020). Those gas elements with large x_0 pass by the planet (passing; shown in red), while those with small x_0 move along horseshoe orbits (horseshoe; shown in green). Some of the streamlines between passing and horseshoe regions reach within $r = 0.2r_H$ (accreting; shown in dark blue)^{*2}, and others enter the planet's Hill sphere

^{*2}For the low-mass cases, we found that the gas streamlines which reach within $r = 0.2r_H$ also reaches within $r = 0.07r_B$ ($< 0.2r_H$) and the same accretion bands are obtained for both criteria of accretion. This means that the gas which reaches within $r = 0.2r_H$ loses its angular momentum at the shock surface on the

(whose surface is defined by the equipotential surface with $\hat{\Phi} = 0$ in Equation (2.4)) and then escape from it (recycling; shown in light blue). We confirmed the three-dimensional structure of gas accretion, which was reported by previous works that examined cases for $M_p \sim M_{\text{Jup}}$ (Machida et al. 2008, 2010, Tanigawa et al. 2012, Gressel et al. 2013, Szulágyi et al. 2014, Schulik et al. 2020) as well as lower-mass ($\sim$ Super-Earth) cases (Wang et al. 2014, Kuwahara et al. 2019, Fung et al. 2019, Lambrechts et al. 2019). Figure 2.6 shows the streamlines with (a) $\hat{z}_0 = 0.5$ and (b) $\hat{z}_0 = 0$, respectively, for $\hat{r}_H = 1.36$ ($M_p = 1M_{\text{Jup}}$). The off-midplane gas elements encounter the planetary shock and change their direction slightly upward. Then, they accrete onto the CPD (Figure 2.6a). On the other hand, the gas elements which originate from the midplane cannot enter the Hill sphere, because radially outward flow dominates at the midplane (Figure 2.6b; see also Figure 2 of Tanigawa et al. 2012). It should be noted that the path of the accreting streamline likely depends on temperature structure. According to global radiative-hydrodynamic simulations (Schulik et al. 2020), the spiral arm tilt, which depends on the vertical structure of temperature, controls the direction of accreting gas flow. The direction change observed in Figure 2.6a is less clear than the one found in Schulik et al. (2020). This is probably due to the difference in the temperature distribution. In our isothermal simulation, the vertical distribution of temperature does not have a gradient, which likely affects the tilt of the spiral arms.

Figure 2.7 shows radial and vertical distributions of each type of streamline at the starting points (x_0, z_0) for planetary masses of $\hat{r}_H = 0.8, 1.0$, and 1.36 ($M_p = 0.2, 0.4$, and $1M_{\text{Jup}}$), respectively. In all these cases, we found that the accretion bands (the dark blue regions) do not exist near the midplane ($z_0 \simeq 0$) but are distributed above the midplane continuously in the z -direction in a zonal pattern. We also found that the radial (x -direction) width of the accretion band increases as the planetary mass increases. This indicates that a more massive planet can acquire gas and dust particles from a radially wider region in the PPD.

Next, we evaluate the radial width of the accretion band and its dependence on planetary mass. Let the non-dimensional radial width of accretion band at a scaled starting altitude $\hat{z}_0$ be $\hat{w}(\hat{z}_0)$. Assuming the hydrostatic equilibrium in the z -direction, the vertical density distribution of gas is given by

$$\hat{\rho}(z) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{\hat{z}^2}{2}\right). \quad (2.12)$$

We take an average of $\hat{w}(\hat{z}_0)$ weighted by the above vertical density distribution as

$$\bar{\hat{w}} = \frac{\int_0^{\hat{z}_{0,\text{max}}} \hat{w}(\hat{z}_0) \exp\left(-\frac{\hat{z}_0^2}{2}\right) d\hat{z}_0}{\int_0^{\hat{z}_{0,\text{max}}} \exp\left(-\frac{\hat{z}_0^2}{2}\right) d\hat{z}_0}, \quad (2.13)$$

where we assumed $\hat{z}_{0,\text{max}} = 3$ because contribution of gas accretion from $\hat{z}_0 > 3$ is negligible.

Figure 2.8 shows the dependence of the averaged width of the accretion band as a function of $\hat{r}_H$, which depends on the planetary mass as shown in Equation (2.7). The crosses are obtained from our numerical results. The dashed line is the fitting function for the low-mass regime:

$$\bar{\hat{w}} = 0.065\hat{r}_H^{1/2} = 0.054 \left(\frac{M_p}{M_c}\right)^{1/6} \left(\frac{a}{h_g}\right)^{1/2}, \quad (2.14)$$

CPD and flows toward the inner region of the CPD (see also Figure 15 in Tanigawa et al. 2012).

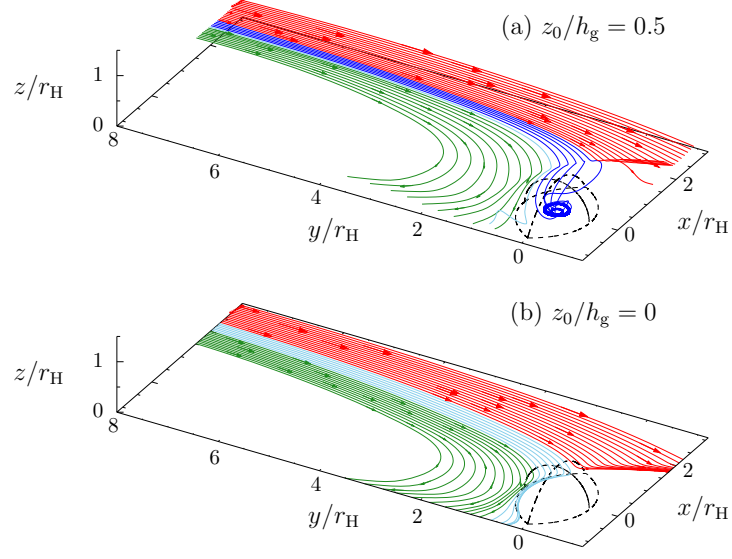


Figure 2.6: Classification of streamlines in the cases of (a) $z_0/h_g = 0.5$ and (b) $z_0/h_g = 0$ for the model with $\hat{r}_H = 1.36$ ($M_p = 1M_{\text{Jup}}$). Colors show the types of streamlines. Red: passing (Keplerian shear flow), green: horseshoe (moving along a horseshoe orbit), dark-blue: accreting (reaching within $r = 0.2r_H$), light-blue: recycling (streamlines which enter the planet's Hill sphere and then escape from it). The lemon-shaped region enclosed by the dashed line in each panel is the planet's Hill sphere (its surface is defined by $\hat{\Phi} = 0$ in Equation (2.4))

and the solid line shows the fitting function for the high-mass regime:

$$\bar{w} = 0.12\hat{r}_H^3 = 0.04 \left(\frac{M_p}{M_c} \right) \left(\frac{a}{h_g} \right)^3. \quad (2.15)$$

Thus, planetary-mass dependences of the averaged accretion band width are different between the low-mass and high-mass regimes; $\bar{w} \propto r_H^{1/2} \propto M_p^{1/6}$ for $\hat{r}_H \leq 0.8$ ($M_p \leq 0.2M_{\text{Jup}}$) and $\bar{w} \propto r_H^3 \propto M_p$ for $\hat{r}_H \geq 0.8$ ($M_p \geq 0.2M_{\text{Jup}}$), respectively. Note that the planetary-mass dependence of $\bar{w}$ for the low-mass regime has larger uncertainties due to the small number of cases we examined.

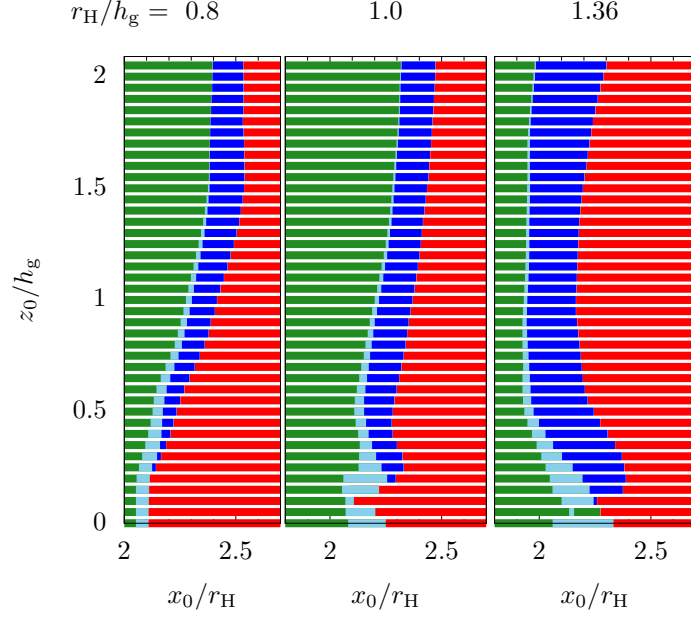


Figure 2.7: Classification of initial positions (x_0, z_0) of streamlines of the gas flow at $y/h_g = 12$ and $x > 0$ by their final destinations. The initial radial position x_0 is scaled by r_H , while z_0 is scaled by the gas scale height h_g . Colors show the types of streamlines. Red: passing (Keplerian shear flow), green: horseshoe (moving along a horseshoe orbit), dark blue: accreting (reaching within $r = 0.2r_H$; we call this region accretion band), light blue: recycling (streamlines which enter the planet's Hill sphere and then escape from it). Three cases with $\hat{r}_H = 0.8, 1.0, 1.36$ ($M_p = 0.2, 0.4$, and $1M_{\text{Jup}}$) are shown.

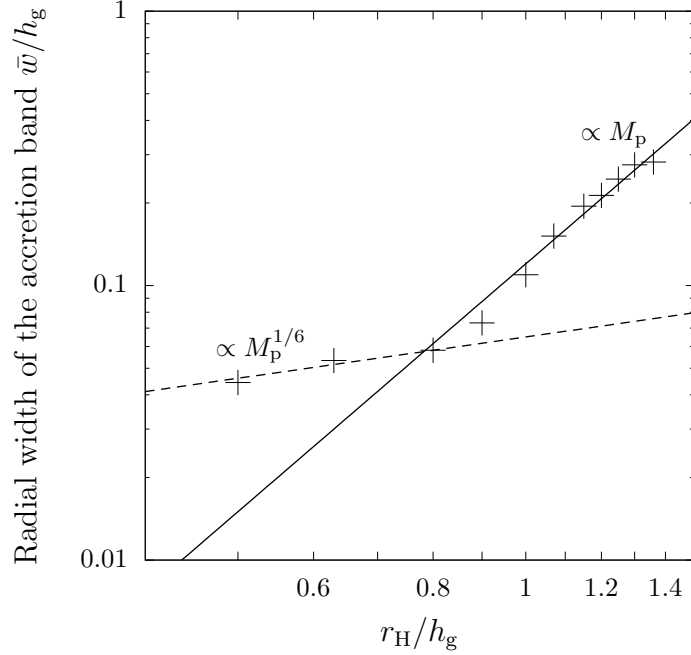


Figure 2.8: Dependence of vertically averaged width of the accretion band $\bar{w}/h_g$ on $\hat{r}_H = r_H/h_g$. The dashed and solid lines show the functions denoted by Equations (2.14) and (2.15), respectively.

2.3.4 Mass accretion rate onto circumplanetary disks

Vertical structure of accreting gas

As shown in the previous section, the gas accreting into the CPD comes from high altitudes, and the vertical structure of the accretion band depends on the planetary mass. On the other hand, the gas density in the unperturbed PPD decreases with increasing altitude. In order to understand which vertical part of the PPD contributes most to the accretion into the CPD, we examine the mass accretion rate as a function of the initial altitude $\hat{z}_0$ of the accreting gas.

Figure 2.9 shows the mass accretion rate per unit length in the z -direction of the gas originating from an altitude $\hat{z}_0(> 0)$ into the CPD defined as

$$\hat{f}_{\text{CPD}}(\hat{z}_0) = \int_{\hat{x}_{0,\min}(\hat{z}_0)}^{\hat{x}_{0,\max}(\hat{z}_0)} \hat{\rho}(\hat{x}_0, \hat{z}_0) \hat{v}(\hat{x}_0, \hat{z}_0) d\hat{x}_0, \quad (2.16)$$

where $\hat{x}_{0,\min}$ and $\hat{x}_{0,\max}$ are the values of $\hat{x}_0$ at the inner and outer boundaries of the accretion band at $\hat{z}_0$, respectively. Equation (2.16) includes only the gas accreting from $x_0 > 0$ and $z_0 > 0$. We show the plots of $\hat{f}_{\text{CPD}}(\hat{z}_0)$ for three cases of different planetary masses corresponding to $\hat{r}_H = 0.8, 1.0$, and 1.36 . We found that a major contribution to the mass accretion comes from lower altitudes for higher planetary masses; the peak of the mass accretion rate is at $z_0/h_g \simeq 1.0, 0.6$, and 0.3 for $\hat{r}_H = 0.8, 1.0$, and 1.36 , respectively. This reflects the vertical structure of the accretion band (see Figure 2.7), which becomes wider at lower z_0 and is distributed down to lower altitudes with increasing planetary mass. We also show in Figure 2.9 the cumulative distribution of the mass accretion rate normalized by the total mass accretion rate with the dashed lines. We found that about 80% of gas accreting into the CPD comes from $z_0 \lesssim 1.5h_g$, and the contribution from lower altitudes increases with increasing planetary mass, as we described above. For example, the contribution from $z \leq 0.3h_g$ is $\simeq 1.6\%$, $\simeq 10\%$, and $\simeq 20\%$ for $\hat{r}_H = 0.8, 1.0$, and 1.36 , respectively.

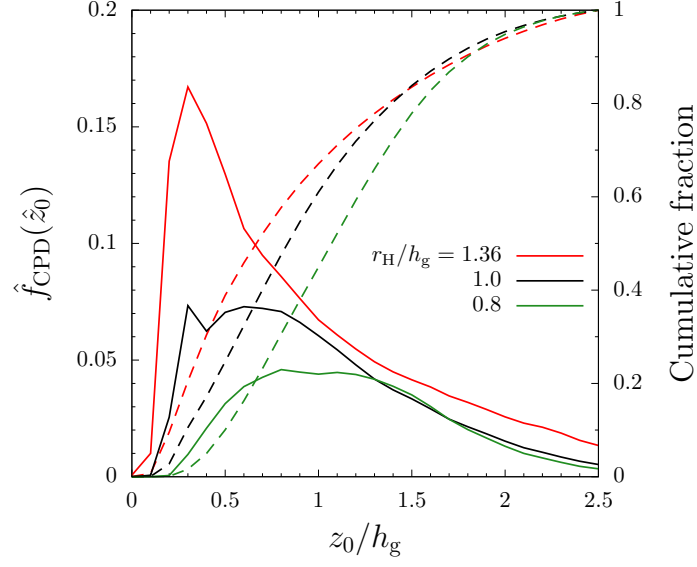


Figure 2.9: Mass accretion rate per unit length in the z -direction of the gas originates from an altitude $\hat{z}_0$ into the CPD defined by Equation (2.16). Only the gas accreting from $x_0 > 0$, $z_0 > 0$ is considered. The dashed lines show the cumulative distribution, which is normalized by the value at $z_0/h_g = 2.5$. Colors show the different planetary mass case; green shows $\hat{r}_H = 0.8$ ($0.2M_{\text{Jup}}$), black shows $\hat{r}_H = 1.0$ ($0.4M_{\text{Jup}}$), and red shows $\hat{r}_H = 1.36$ ($1M_{\text{Jup}}$), respectively.

Mass accretion rate evaluated from our simulation

As shown in Figure 2.7, only part of the gas entering the planet’s Hill sphere comes sufficiently close to the planet to accrete into the CPD, and the rest is expelled back to the PPD as part of the meridional circulation (e.g., Tanigawa et al. 2012, Morbidelli et al. 2014, Fung & Chiang 2016). Thus, the mass accretion rate of the gas into the CPD ($\dot{M}_{\text{acc,CPD}}$) is generally smaller than that into the Hill sphere ($\dot{M}_{\text{acc,Hill}}$), and the ratio $\dot{M}_{\text{acc,CPD}}/\dot{M}_{\text{acc,Hill}}$ is an important quantity when considering the delivery of small dust particles coupled to the gas into the CPD as building blocks of satellites. Here we calculate $\dot{M}_{\text{acc,CPD}}$ and $\dot{M}_{\text{acc,Hill}}$ from the above analysis of the streamlines and using the following equations:

$$\dot{M}_{\text{acc,CPD}} = 4 \int_0^{\hat{z}_{0,\text{max}}} \hat{f}_{\text{CPD}}(\hat{z}_0) d\hat{z}_0 \quad (2.17)$$

and

$$\dot{M}_{\text{acc,Hill}} = 4 \int_0^{\hat{z}_{0,\text{max}}} \hat{f}_{\text{Hill}}(\hat{z}_0) d\hat{z}_0, \quad (2.18)$$

where $\hat{f}_{\text{Hill}}(\hat{z}_0)$ is the mass accretion rate into the Hill sphere per unit length in the z -direction, which is obtained by using both recycling and accreting streamlines in a similar calculation to Equation (2.16) (see Figures 2.6 and 2.7). The factor of four is multiplied in Equation (2.17) and Equation (2.18) to account for the symmetry about the $x = 0$ and $z = 0$ planes. We did not adopt the sink cell. Thus, in the quasi-steady state of the gas flow in our simulations, the accreted gas accumulates in the CPD while part of it is expelled back toward the protoplanetary disk as an outflow near the midplane of the CPD (the top panel of Figures 2.4 and 2.5). In order to precisely derive the amount of the gas that is accreted in the CPD but then expelled back toward the protoplanetary disk as an outflow from the midplane region of the CPD, we will need to investigate the long-term viscous evolution of the CPD. However, it is difficult to investigate it in our present simulation where the gas is assumed to be inviscid and is beyond the scope of the present work. Thus, in the present work, we derived the accretion rate onto the CPD from the analysis of the streamlines that reach within $r = 0.2r_{\text{H}}$ (i.e., the dark blue region in Figure 2.7).

In Figure 2.10, we show the planetary mass dependence of $\dot{M}_{\text{acc,CPD}}$ and $\dot{M}_{\text{acc,Hill}}$ (top panel), and the ratio $\dot{M}_{\text{acc,CPD}}/\dot{M}_{\text{acc,Hill}}$ (bottom panel). We found that $\dot{M}_{\text{acc,Hill}}/\Sigma_0 h_{\text{g}}^2 \Omega_{\text{K}} \simeq 0.4$ when $\hat{r}_{\text{H}} = 1$, which is consistent with Tanigawa et al. (2012, their Figure 14), who found that $\dot{M}_{\text{acc,Hill}}/\Sigma_0 h_{\text{g}}^2 \Omega_{\text{K}} \simeq 0.2$ for the mass accretion rate onto the $z > 0$ surface of the CPD for $\hat{r}_{\text{H}} = 1$. We also found that $\dot{M}_{\text{acc,CPD}}/\dot{M}_{\text{acc,Hill}} \simeq 0.4$ regardless of the planetary mass. This means that gas accretion rate onto the CPD can be estimated from that into the Hill sphere in global simulation at least in the planetary mass range corresponding to $\hat{r}_{\text{H}} = 0.5 - 1.36$, as long as the resolution of the simulation is sufficient to resolve the gas flow on the Hill-radius scale. Also, the fact that the ratio $\dot{M}_{\text{acc,CPD}}/\dot{M}_{\text{acc,Hill}}$ is nearly independent of the planetary mass indicates that this ratio is insensitive to whether the gap opens or not, probably because it is determined by the distributions of the accretion band and recycling region (Figure 2.7), which is likely to be insensitive to the gap depth. It should be noted that absolute values of the mass accretion rates shown in Figure 2.10 depend on the gap depth at the planet’s orbit, which depends on numerical settings such as simulation time and resolution (e.g., Kanagawa et al. 2017). Thus, in § 2.4.1, we will discuss the corrected values of mass accretion rate using the gap model obtained from global hydrodynamic simulations (Kanagawa et al. 2015).

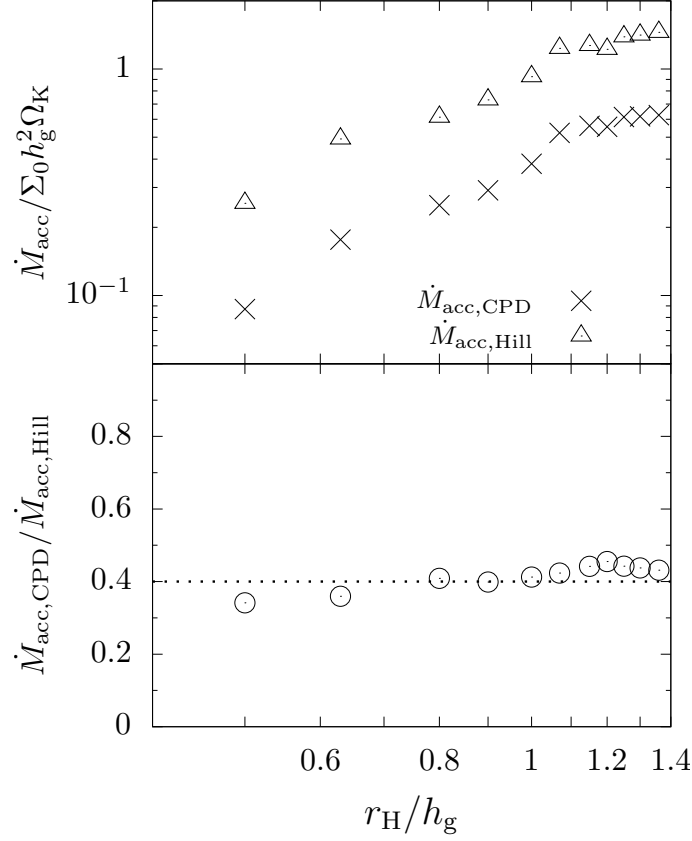


Figure 2.10: Top panel: Dependence of non-dimensional mass accretion rates into the CPD ($\dot{M}_{\text{acc,CPD}}$; crosses) and the Hill sphere ($\dot{M}_{\text{acc,Hill}}$; triangles) on $\hat{r}_H = r_H / h_g$. Bottom panel: The ratio $\dot{M}_{\text{acc,CPD}} / \dot{M}_{\text{acc,Hill}}$ as a function of $\hat{r}_H$. The dotted line represents $\dot{M}_{\text{acc,CPD}} / \dot{M}_{\text{acc,Hill}} = 0.4$.

2.4 Discussions

2.4.1 Semi-analytical formulae of mass accretion rate

Here, we consider a physical interpretation of the planetary-mass dependence of mass accretion rates onto the CPD and derive semi-analytical formulae by combining our results with the gap model obtained from global hydrodynamic simulations (Kanagawa et al. 2015), because our local simulation cannot reproduce the gap depth accurately as we mentioned before.

Let us consider the gas flowing through the area of the accretion band at $(x, y) = (x_{\text{ab}}, L_y/2)$, where x_{ab} is a typical value of the x -coordinate of the accretion band. In the coordinate system rotating with the planet, the velocity of the gas passing the area of the accretion band is $(3/2)x_{\text{ab}}\Omega_K$ assuming the Keplerian shear flow at $y = L_y/2$. Then, we can express the mass accretion rate onto the CPD as

$$\dot{M}_{\text{acc,CPD}} = D \Sigma_{\text{g,ab}}, \quad (2.19)$$

where $\Sigma_{\text{g,ab}}$ is the surface density of the gas at $(x, y) = (x_{\text{ab}}, L_y/2)$, and D is the "accre-

tion area” of the protoplanetary disk per unit time (Tanigawa & Tanaka 2016). Tanigawa & Tanaka (2016) used the expression for D for the gas accretion onto a growing planet based on the isothermal and inviscid two-dimensional hydrodynamic simulation of Tanigawa & Watanabe (2002).^{*3} Here we assume that D for the mass accretion rate on the CPD can be expressed in terms of the averaged accretion band width obtained from our three-dimensional hydrodynamic simulation (§ 2.3.3) as

$$D = 2 \times \frac{3}{2} x_{\text{ab}} \Omega_K \bar{w}. \quad (2.20)$$

The factor of two is multiplied in the r.h.s. of Equation (2.20) to account for the symmetry about $x = 0$ plane. For simplicity, we assume $x_{\text{ab}} = 2.2r_{\text{H}}$, regardless of the planetary mass (Figure 2.7).

Substituting $x_{\text{ab}} = 2.2r_{\text{H}}$ and the expression for $\bar{w}$ using Equation (2.14) or (2.15) into Equation (2.20), we obtain

$$D = 0.25 \left(\frac{M_{\text{p}}}{M_{\text{c}}} \right)^{1/2} \left(\frac{a}{h_{\text{g}}} \right)^{-1/2} a^2 \Omega_K \quad \text{for } 0.5 \leq \hat{r}_{\text{H}} \leq 0.8 \quad (2.21)$$

and

$$D = 0.18 \left(\frac{M_{\text{p}}}{M_{\text{c}}} \right)^{4/3} \left(\frac{a}{h_{\text{g}}} \right)^2 a^2 \Omega_K \quad \text{for } 0.8 \leq \hat{r}_{\text{H}} \leq 1.36. \quad (2.22)$$

In Figure 2.11, we plot the values of D calculated by Equations (2.21) and (2.22), and compare them with the results of our hydrodynamic simulation, where D is derived by $\dot{M}_{\text{acc,CPD}}/\Sigma_{\text{g,ab,sim}}$ with $\Sigma_{\text{g,ab,sim}}$ being the surface density at the accretion band obtained by our hydrodynamic simulation (Figure 2.13). For comparison, we also plot the values of D obtained from the two-dimensional simulation by Tanigawa & Watanabe (2002), which was used in Tanigawa & Tanaka (2016). We found that the results of our hydrodynamic simulation can be well reproduced by Equation (2.22) in the high-mass regime, while they somewhat deviate from those calculated by Equation (2.21) in the low-mass regime. This indicates that our model given by Equations (2.19) and (2.22) reproduces our numerical results well in the high-mass regime, but it is not satisfactory for the low-mass regime. The assumption that x_{ab} is independent of M_{p} may be too simple in the low-mass regime, and effects of different flow patterns for cases with $r_{\text{H}} < h_{\text{g}}$ would also be important. In any case, it is difficult to construct an accurate model in the low-mass regime from our results, because in the present work we mainly focus on large-mass planets with a CPD in relation to satellite formation, and we ran only a few simulations for the low-mass regime. It should be noted that the planetary-mass dependence given by Equation (2.22) ($\propto M_{\text{p}}^{4/3}$) is consistent with the one obtained by the two-dimensional simulation (Tanigawa & Watanabe 2002). Although the qualitative behavior of accretion flow onto the CPD such as the strength of shocks is quite different between the two- and three-dimensional cases, the mass dependence of the accretion rates remains the same.

^{*3}Tanigawa & Watanabe (2002) defined the mass accretion rate by the time-averaged mass flux across the inner sink boundary at $r = 0.05r_{\text{H}}$.

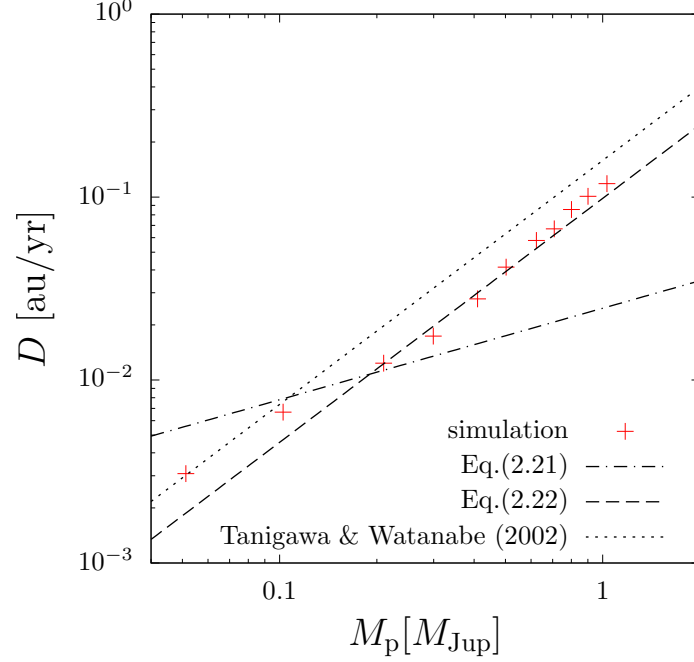


Figure 2.11: Planetary-mass dependence of D obtained by our hydrodynamic simulation ($= \dot{M}_{\text{acc,CPD}}/\Sigma_{\text{g,ab,sim}}$; red crosses) and the one calculated from Equations (2.21) (dot-dashed line) and (2.22) (dashed line). The values of D obtained by two-dimensional simulation of Tanigawa & Watanabe (2002) are also plotted (dotted line). Following Tanigawa & Tanaka (2016), we assume $a = 5.2$ au.

In the following, we assume that our simulation results can be approximated by Equations (2.19) and (2.22) for the whole range of planetary-mass we examined, and derive mass accretion rate using the empirical formula for the gap surface density obtained from global simulations (Kanagawa et al. 2015) given as

$$\frac{\Sigma_{\text{min}}}{\Sigma_0} = \frac{1}{1 + 0.04K} \quad (2.23)$$

with

$$K = \left(\frac{M_p}{M_c}\right)^2 \left(\frac{h_g}{a}\right)^{-5} \alpha^{-1}, \quad (2.24)$$

where Σ_{min} is the surface density at the bottom of the gap. We assume $\Sigma_{\text{g,ab}} = \Sigma_{\text{min}}$ because $x_{\text{ab}} = 2.2r_H$ is located near the bottom of the gap.

In Figure 2.12, we plotted semi-analytical formula obtained from Equation (2.19) and Equation (2.22) (red line), and our simulation results. Our simulation results derived by Equation (2.17) are shown with the blue open circles (raw values), and those corrected to reproduce the true gap depth by multiplying by $\Sigma_{\text{min}}/\Sigma_{\text{g,ab,sim}}$ (corrected values) are shown with the green filled circles. We find that the semi-analytical formula for the mass accretion rate onto the CPD we obtained can reproduce the numerical results well in the high-mass regime, although they somewhat underestimate the numerical results in the low-mass regime. In the high-mass regime, the planetary-mass dependence of our formula is consistent with the accretion rate onto the planet derived in Tanigawa & Tanaka (2016), but

the absolute values of the accretion rates derived from our three-dimensional simulation are about 60% of those obtained in Tanigawa & Tanaka (2016).

Ginzburg & Chiang (2019) argued that, after the onset of runaway gas accretion but when the planet's Hill radius is still smaller than the disk scale height (i.e., $\hat{r}_H < 1$ in our simulations), the gas accretion rate is expected to match the Bondi accretion rate ($\propto M_p^2$) rather than the empirical formula obtained from the results of hydrodynamic simulations ($\propto M_p^{4/3}$; Tanigawa & Tanaka 2016) in the limit of low planetary mass ($r_B \ll r_H$), because the envelope boundary should be approximately spherically symmetric and the Keplerian shear velocity at r_B is negligible in such a case. It should be noted that our results derived on the basis of the analysis of the accretion bands obtained from hydrodynamic simulations cannot be applied to such low-mass cases.

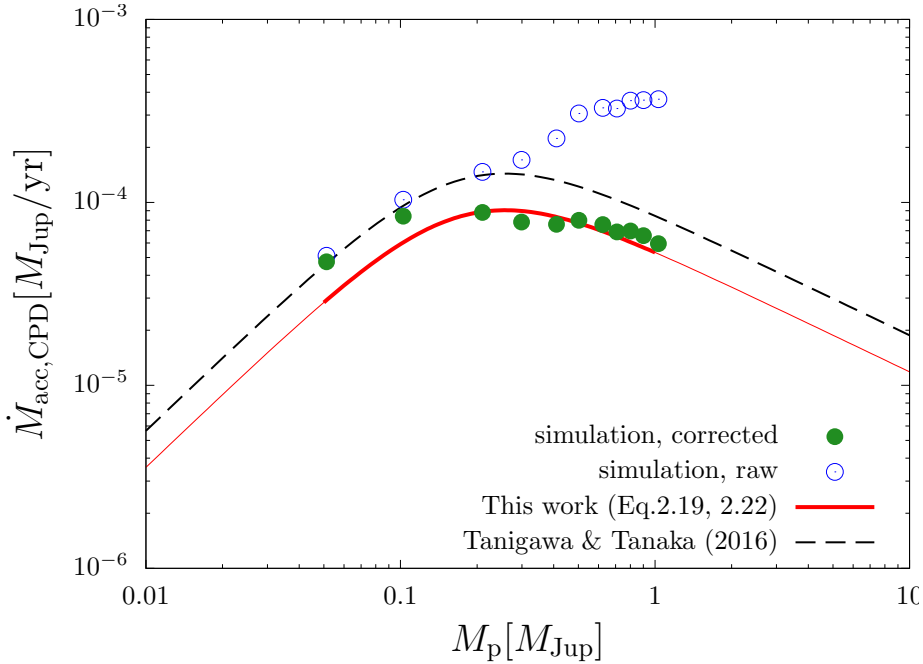


Figure 2.12: Comparison of the mass accretion rates obtained by our hydrodynamic simulation (marks) and semi-analytical formulae (lines). The red line represents our semi-analytic formula (Equations (2.19) and (2.22)), and the dashed line is that derived by Tanigawa & Tanaka (2016) using the results of two-dimensional hydrodynamic simulation. The raw values of our simulation results derived by Equation (2.17) are shown with the blue open circles, and those corrected by multiplying by $\Sigma_{\min}/\Sigma_{\text{g,ab,sim}}$ are shown with the green filled circles. Thin lines are the extrapolation of our formulae beyond the mass range we examined with our simulation. $a = 5.2$ au, $\Sigma_0 = 1.4 \times 10^3$ kg m $^{-2}$, and $\alpha = 4 \times 10^{-3}$ are assumed for direct comparison with Figure 1 in Tanigawa & Tanaka (2016).

2.4.2 Comparisons with previous works on gas accretion band

Some previous works using high resolution local simulation also reported the increase of radial width of the gas accretion band as the planet mass increases. Tanigawa & Watanabe (2002) performed two-dimensional hydrodynamic simulations and found that the radial width of the accretion band increases as the planet becomes more massive. Their detailed analysis of streamlines showed that energy dissipation at the spiral shock around the planet determines the radial width of the accretion band. The energy dissipation increases as the planet becomes more massive. However, our three-dimensional simulations did not show such significant energy dissipation at the spiral shock around the planet. For the three-dimensional accretion, energy dissipation at the shock surface on the CPD is much stronger than that at the spiral arm of the planet (see Figures 10 and 11 in Tanigawa et al. 2012). The structure of the accreting flow in the three-dimensional simulation is qualitatively different from the two-dimensional one. Further studies are needed to explain the planetary-mass dependence of accretion band width in the three-dimensional case with a simple model.

Although the planetary-mass dependence of accretion band width in the three-dimensional case is also examined by Machida et al. (2010), their definition of the accretion band width is different from ours. They defined the width by the difference between $x_{0,\min}$ and $x_{0,\max}$ defined for the whole accretion area in the $x_0 - z_0$ plane, without measuring the radial width of the accretion band at each altitude. The z -dependence of the accretion band width is important when discussing dust accretion onto the CPD (e.g., Homma et al. 2020) because vertical distribution of dust particles varies with turbulence strength in the PPD and deviates from gas distribution unless turbulence in the PPD is sufficiently strong.

2.4.3 Effects of thermodynamics

In this study, we use the isothermal equation of state (EOS). In the late stage of planet formation, the gas surface density is expected to be low. Fluid in low-density regions mainly controls the accreting gas flow, and isothermal assumption should be valid in this region. We note that some regions near the midplane could be optically thick and not well-modeled by isothermal gas because the gap depth is moderately deep in our mass range (Figure 2.13 in Appendix).

Fung et al. (2019) showed that the flow patterns are similar between isothermal and adiabatic cases when planetary mass is large enough ($\hat{r}_H \geq 1.0$). This is because CPD dynamics are dictated by gravity, and the effect of EOS becomes small. For $\hat{r}_H < 1.0$, on the other hand, the gravity of the planet is not so large, and EOS may affect the flow pattern around the planet. Machida et al. (2010) investigated thermal effects on mass accretion rate and found that mass accretion rates with the isothermal and adiabatic EOSs are almost the same when planetary mass is small ($\hat{r}_H \leq 1.0$). However, its planetary-mass dependence is slightly different for $\hat{r}_H \geq 1.0$, and the isothermal case showed stronger dependence on planetary mass. This trend seems different from Fung et al. (2019).

As we mentioned in § 2.3.3, global radiation hydrodynamic simulations of Schulik et al. (2020) showed that the vertical temperature gradient causes the spiral arm tilt, which changes the direction of accreting flow. This indicates that the vertical temperature gradient likely affects the gas accretion onto CPD. Thus, analysis of the structure of the gas accretion band onto CPD with more realistic conditions is desirable (e.g., Szulágyi et al. 2016, 2017, Fung et al. 2019).

2.4.4 Effects of Other Numerical Settings

Settings of a numerical domain can affect the circumplanetary structure and gas accretion. Using global simulation, Gressel et al. (2013) reported that the CPD can have a non-axisymmetry structure, the side facing the central star being thicker. In contrast, the CPD of our local simulation is roughly axisymmetry around the planet. The non-axisymmetry in the global case may lead to different structures of the gas accretion bands in regions interior and exterior to the planet's orbit. However, the basic characteristics of the structure of gas flow near the CPD (i.e., vertical accreting flow and outflow in the midplane) should be similar in both regions.

The radius of the CPD can depend on the effective viscosity (sum of the physical and the numerical viscosities). Szulágyi et al. (2014) showed that the larger effective viscosity tends to produce a larger CPD. In our inviscid simulation, we found that the CPD radius is about $0.2r_H$ for the massive planet cases and $0.08r_B$ for the small planet cases, but these values may become larger for a viscous fluid. However, the qualitative results such as the CPD radius being proportional to the planet's Hill radius and the Bondi radius for massive and small planets, respectively, are likely not to change.

2.5 Conclusions

We performed three-dimensional high-resolution hydrodynamic simulations to investigate the gas flow in the local region around the planet. The main purpose of the present work was to understand the planetary mass dependence of the accreting gas flow onto the CPD, because it is important for delivery of satellite building blocks to the CPD around planets with various masses and was not reported in the previous work (Tanigawa et al. 2012). We performed simulations for $\hat{r}_H = r_H/h_g = 0.5 - 1.36$, corresponding to the planetary masses of $0.05M_{\text{Jup}} - 1M_{\text{Jup}}$ at the current Jovian orbit for the MMSN model (Hayashi 1981). The main results are as follows:

1. The radius of the CPD is proportional to the planet's Hill sphere for the massive planet ($\hat{r}_H \gtrsim 0.8$), while it is proportional to the Bondi radius for the small planet ($\hat{r}_H \lesssim 0.8$). This is consistent with Fung et al. (2019).
2. We examined the radial and vertical distribution of source points of streamlines that accrete onto the CPD. We found that source points of accreting streamlines are continuously distributed above the midplane in the vertical direction (we call this region accretion band). The radial width of the accretion band increases as the planetary mass increases. The width $\bar{w}$ is proportional to the planetary mass for the high-mass regime ($\hat{r}_H \gtrsim 0.8$), while it is proportional to 1/6 power of the planetary mass for the small planet cases ($\hat{r}_H \lesssim 0.8$).
3. We found that the ratio of the mass accretion rate onto the CPD and that into the Hill sphere is about 0.4 regardless of the planetary mass. This means that the gas accretion rate onto the CPD can be estimated from that into the Hill sphere in global simulation as long as the resolution of the simulation is sufficient to resolve the gas flow on the Hill-radius scale.

4. We derived semi-analytical formulae by combining our results with the gap model obtained from global hydrodynamic simulations (Kanagawa et al. 2015). Comparing with the semi-analytical formula obtained using two-dimensional simulation results (Tanigawa & Tanaka 2016), in the high-mass regime ($M_p \gtrsim 0.2M_{\text{Jup}}$), we found that the values of the accretion rates derived from our three-dimensional simulation are about 60% of those obtained from the two-dimensional case. In contrast, the mass dependence of the accretion rates remains the same between the two- and three-dimensional cases, although the qualitative behavior of accretion flow onto the CPD such as the strength of shocks is quite different between the two cases. We also found that the mass dependence of the accretion rate is different between the two- and three-dimensional cases for the low-mass regime ($M_p \lesssim 0.2M_{\text{Jup}}$), but our semi-analytical model is too simple to reproduce the numerical results for the low-mass regime and further studies are needed to construct a more accurate model.

When dust particles are small and strongly coupled with the accreting gas, the mass accretion rate of dust particles should be strongly influenced by the gas. Since actual motion of dust particles is expected to decouple from the gas (e.g., Homma et al. 2020), orbital integration of particles is needed to study supply of dust onto CPD. We will report results of orbital calculation of dust particles in such cases in Chapter 3.

In this work, we focused on planets whose mass is below the Jovian mass. However, more massive planets have been observed beyond the Solar system (e.g., Liu & Ji 2020). Understanding satellite formation around exoplanet systems is important to construct a more general theory of satellite formation. Recently, some CPD candidates have been found (Ginski et al. 2018, Isella et al. 2019, Tsukagoshi et al. 2019, Benisty et al. 2021) as well as exomoon candidates (e.g., Teachey & Kipping 2018, Kipping et al. 2022). Further studies of gas and dust accretion onto the CPD of planets with various masses will help us understand satellite formation in our Solar System as well as in exoplanet systems.

2.6 Appendix: Gas Surface Density at the accretion band

The planetary-mass dependence of the gas surface density at the accretion band, $\Sigma_{\text{g,ab,sim}}$, is shown in Figure 2.13 with red crosses. $\Sigma_{\text{g,ab,sim}}/\Sigma_0$ has values near unity in the low-mass limit, i.e., gap opening is little progressed in this regime. On the other hand, it has a planetary-mass dependence of $\Sigma_{\text{g,ab,sim}} \propto M_p^{-1}$ in the high-mass regime ($\hat{r}_H \gtrsim 1.0$). The deviation between our results and those obtained from the empirical formulae obtained by global simulation, Equations (2.23) and (2.24), (dot-dashed curve) increases with increasing planetary mass. This deviation is caused by the use of local simulation in the present work.

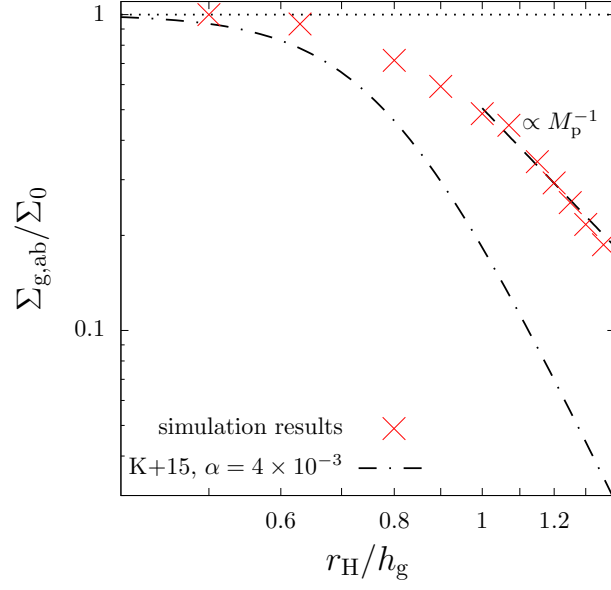


Figure 2.13: Dependence of surface density at the accretion band $\Sigma_{g,ab}$, i.e., surface density of gas at $(x, y) = (2.2r_H, L_y/2)$, on $\hat{r}_H = r_H/h_g$. The dashed line shows the function proportional to M_p^{-1} . The dotted-dashed curve shows surface density at the gap bottom derived by Kanagawa et al. (2015) for the case of $\alpha = 4 \times 10^{-3}$.

Chapter 3

Delivery of Dust Particles from the Protoplanetary Disk onto the Circumplanetary Disk of Giant Planets

*2

3.1 INTRODUCTION

Massive regular satellites, such as the Galilean satellites and Titan, are thought to be formed by accumulation of solids in circumplanetary disks (CPDs), gaseous disks formed around giant planets when the planet accretes gas of the protoplanetary disks (PPDs). In early models of satellite formation around Jupiter and Saturn, their CPDs were assumed to be isolated from the PPD. The total dust mass in each CPD is assumed to be consistent with the total current mass of the satellites in each system, which is a similar concept to the minimum mass solar nebula (MMSN) model (Lunine & Stevenson 1982). Mosqueira & Estrada (2003a,b) extended this model by considering CPDs composed of an optically thick inner region and an optically thin outer region. Satellite formation in such CPDs has been recently examined in detail by Miguel & Ida (2016). They found that the high gas density in the inner disk leads to very rapid migration of satellitesimals, and it is difficult to form the current Galilean satellites in such a CPD.

On the other hand, Canup & Ward (2002) proposed the gas-starved disk model for the CPD, in which gas and solids are continuously supplied from the PPD. Canup & Ward (2006) showed that the gas-starved disk can reproduce the common mass ratio of the satellite system to the host planet observed for giant planets in the solar system. In addition, the hydrodynamic simulations showed that a CPD is naturally formed around a sufficiently massive planet during its gas accretion phase (e.g., Tanigawa & Watanabe 2002, Machida et al. 2008, Tanigawa et al. 2012, Szulágyi et al. 2014, 2016, 2017). Thus the picture of the gas-starved disk has been widely accepted. Therefore, various studies of satellite formation have been conducted with such CPDs (e.g., Canup & Ward 2002, 2006, Sasaki et al. 2010, Ogiwara & Ida 2012). Recently, a model of satellite formation in a decretion disk, which

*2The content of this chapter is an author-created, un-copyedited version of an article submitted to The Astrophysical Journal (Maeda et al., in revision). IOP Publishing Ltd is not responsible for any errors or omissions in this version of the manuscript or any version derived from it.

has nearly vertical inflow in the inner part and outflow near the midplane, has also been proposed (Batygin & Morbidelli 2020).

In such models of satellite formation, the total amount and the size of solid particles supplied to the CPD are important, because they likely determine the timescale of satellite accretion and the composition of the formed satellites (e.g., Canup & Ward 2002, Ronnet et al. 2017). Fujita et al. (2013) studied capture of kilometer-size and larger planetesimals, and Suetsugu & Ohtsuki (2017) examined their capture and subsequent orbital evolution in the CPD. Such planetesimals can be captured in the inner part of the CPD where the gas density is sufficiently high and the planetesimals suffer strong gas drag. Suetsugu & Ohtsuki (2017) concluded that captured planetesimals would contribute to satellite formation more than the dust supplied with the gas if both the velocity dispersion of the planetesimals and the width of the planetesimal gap in the PPD are sufficiently small. If planetesimals can be captured near the outer edge of the gas gap due to the filtering effect (e.g., Rice et al. 2006), external gravitational perturbation from other planets or planetary embryos would be necessary to deliver them to the CPD (Ronnet et al. 2018). On the other hand, relatively small particles such as pebbles and dust would also be important building blocks of satellites. Shibaike et al. (2019) proposed the so-called slow-pebble-accretion scenario of Galilean satellite formation. In this scenario, a small number of planetesimals captured by the CPD slowly accretes pebbles supplied into the CPD. The scenario proposed by Shibaike et al. (2019) can reproduce most characteristics of the current Galilean satellites if some reasonable parameters are assumed. While many of these studies assumed sufficient solids in the CPD, there are still many unknowns about the supply of solid particles into the CPD.

Since meter-sized and smaller particles are much more susceptible to the effects of gas drag than kilometer-size planetesimals, the gas field around the CPD needs to be taken into account for their delivery into the CPD. High-resolution hydrodynamic simulations showed that only the off-midplane gas in the PPD can accrete onto the CPD and the accretion occurs nearly vertically. In addition, part of the accreted gas flows radially outward through the planet's Hill sphere on the midplane unless the viscosity of the PPD is very small (e.g., Tanigawa et al. 2012, Szulágyi et al. 2014, 2017), which prevents small particles confined in the midplane of the PPD from accreting into the CPD (Tanigawa et al. 2014). Thus, assistance of vertical inflow is important for the delivery of small particles coupled with the gas to the CPD. Homma et al. (2020) investigated the supply to the CPD of solid particles with various sizes distributed vertically in the PPD, considering the gas field around the planet obtained from the local hydrodynamic simulation of Tanigawa et al. (2012). They found that small particles sufficiently stirred up by turbulence in the PPD can accrete onto the CPD with the vertically accreting gas.

However, Tanigawa et al. (2012, 2014) and Homma et al. (2020) only examined the case where the Hill radius of the planet is the same as the scale height of the PPD, which corresponds to a planet with the mass of $0.4M_{\text{Jup}}$ (M_{Jup} is the current mass of Jupiter) at 5.2 au in the case of the MMSN, and the planetary-mass dependence was not investigated. Understanding of the planetary-mass dependence is important for the understanding of the satellite formation around planets with various masses, for example, Jupiter, Saturn, and exoplanets. Also, CPDs of exoplanets have been observed recently (e.g., Isella et al. 2019), and a better understanding of the planetary mass dependence is expected to contribute to modeling of solid delivery into the CPD for comparison with the observations.

In our recent paper (Maeda et al. 2022; Chapter 2), we performed local three-dimensional

high-resolution hydrodynamic simulations for various planetary masses (corresponding to $0.05 - 1M_{\text{Jup}}$ at 5.2 au for the MMSN) with the same numerical code used in Tanigawa et al. (2012) (see also Machida et al. 2008), and revealed the planetary-mass dependence of the source region and mass accretion rate of gas accreting into the CPD. In this chapter, we will examine the planetary-mass dependence of the supply of solid particles into the CPD using the gas fields obtained by Maeda et al. (2022).

The structure of this chapter is as follows. In § 3.2, we will explain basic equations, gas drag calculation, and numerical settings. In § 3.3, we will show the results of orbital calculation, such as initial altitudes and radial locations in the PPD of dust particles captured in the CPD, and capture rates of dust particles. In § 3.4, we will derive the capture rate as a function of dust scale height, and also examine the degree of dust retention in accreting gas into the CPD. We will also derive the dust mass accretion rate onto the CPD and the ratio of dust-to-gas inflow rates by combining our results with the gap models for the surface densities of dust and gas obtained in previous works. We will also discuss model limitations of this study. We will summarize this work in § 3.5.

3.2 METHODS

3.2.1 Basic Equations

We integrate orbits of particles taking account of the effects of the gas flow perturbed by the gravity of a planet, using the methods described in Homma et al. (2020) (see also Tanigawa et al. 2014). We consider a three-body problem for a central star, a planet, and a particle, assuming that the planet is on a circular orbit. We adopt the rotating local Cartesian coordinate system with origin at the planet, the x -axis pointing radially outward, the y -axis in the direction of the planet's orbital motion, and the z -axis in the vertical direction to the PPD midplane. We neglect the curvature of the protoplanetary disk, and define r and R as $r \equiv (x^2 + y^2 + z^2)^{1/2}$ and $R \equiv (x^2 + y^2)^{1/2}$, respectively. When the masses of the planet and the particle are sufficiently smaller than that of the central star and the orbital eccentricity and inclination are small, the motion of the particle relative to the planet can be described by the Hill equations (Nakazawa et al. 1989, Ohtsuki 2012). The Hill equations can be normalized by the planet's Hill radius $r_H = (M_p/(3M_c))^{1/3}a$ and the inverse of orbital angular velocity of the planet $\Omega_K^{-1} = (GM_c/a^3)^{-1/2}$, where M_c , M_p , and a are the masses of the central star and the planet, and the semi-major axis of the planet, respectively. The normalized Hill equations considering gas drag are described as (Fujita et al. 2013, Tanigawa et al. 2014, Homma et al. 2020):

$$\begin{cases} \ddot{\tilde{x}} = 2\dot{\tilde{y}} + 3\tilde{x} - \frac{3\tilde{x}}{\tilde{r}^3} + \tilde{a}_{\text{drag},x}, \\ \ddot{\tilde{y}} = -2\dot{\tilde{x}} - \frac{3\tilde{y}}{\tilde{r}^3} + \tilde{a}_{\text{drag},y}, \\ \ddot{\tilde{z}} = -\tilde{z} - \frac{3\tilde{z}}{\tilde{r}^3} + \tilde{a}_{\text{drag},z}, \end{cases} \quad (3.1)$$

where tildes denote normalized quantities.

Using the gas drag force $\mathbf{F}_{\text{drag}} = -(1/2)C_D\pi r_d^2\rho_g\Delta\mathbf{u}\Delta\mathbf{u}$ and the particle mass m_d , the acceleration due to the gas drag force $\mathbf{a}_{\text{drag}} = \mathbf{F}_{\text{drag}}/m_d$ is expressed in the normalized

notation as

$$\tilde{\mathbf{a}}_{\text{drag}} = -\frac{3}{8}C_D \frac{\rho_g}{\rho_d} \tilde{r}_d^{-1} \Delta \tilde{\mathbf{u}} \Delta \tilde{\mathbf{u}}, \quad (3.2)$$

where C_D , ρ_d , ρ_g , r_d , $\Delta \mathbf{u}$ are the gas drag coefficient, bulk density of the particle (we assume $\rho_d = 10^3 \text{ kg m}^{-3}$), gas density, particle radius, and the velocity of the particle relative to the gas, respectively.

3.2.2 Background Gas Flow

Hydrodynamic Simulations

We use the gas fields obtained by Maeda et al. (2022) (see Chapter 2) with local three-dimensional hydrodynamical simulations to calculate the gas drag force for dust particles. The nested-grid method (e.g., Machida et al. 2005, 2006) is used for the hydrodynamical simulations to examine the gas flow in the vicinity of the CPD with high resolution while considering a wide area around the planet ($x, y \in [-12h_g, 12h_g]$, $z \in [0, 6h_g]$, where h_g is the gas scale height of the PPD). We denote the level of the nested-grid by l , where $l = 1$ corresponds to the whole simulation box. With each increment of the level of the nested-grid, the size of the computational box is reduced by a factor of two, keeping the center of the box and the number of cells the same; the number of the cells for all grid levels is $(n_x, n_y, n_z) = (64, 64, 16)$. We set the maximum grid level to be 11.

An important parameter in our simulation is the Hill radius of the planet normalized by the scale height of the PPD, denoted by

$$\frac{r_H}{h_g} = \left(\frac{M_p}{3M_c} \right)^{1/3} \frac{a}{h_g}. \quad (3.3)$$

Assuming that $M_c = M_\odot$ and the temperature distribution of the PPD is given by the MMSN model ($T = 280 \text{ K } (a/1 \text{ au})^{-1/2}$) (Hayashi 1981), we obtain the relationship between the planetary mass M_p and the parameter r_H/h_g as

$$\frac{M_p}{M_{\text{Jup}}} = 0.41 \left(\frac{M_c}{1M_\odot} \right)^{1/2} \left(\frac{a}{5.2 \text{ au}} \right)^{3/4} \left(\frac{r_H}{h_g} \right)^3. \quad (3.4)$$

Thus, $r_H/h_g = 0.8, 1.0$, and 1.36 correspond to the planetary masses of $M_p = 0.2, 0.4$, and $1.0M_{\text{Jup}}$, respectively. In this work, we will examine these three cases. Note that these cases correspond to the high-mass regime examined in Chapter 2.

Effects of Gas Drag Force

As for the gas drag coefficient C_D , we use the following interpolation formula that reproduces known expressions in limiting cases (see Tanigawa et al. 2014, Homma et al. 2020):

$$C_D = \left[\left(\frac{24}{\mathcal{R}} + \frac{40}{10 + \mathcal{R}} \right)^{-1} + 0.23\mathcal{M} \right]^{-1} + \frac{(2.0 - w_c)\mathcal{M}}{1.6 + \mathcal{M}} + w_c, \quad (3.5)$$

where $\mathcal{R} = 2r_d\Delta u/\nu$ is the Reynolds number, and $\mathcal{M} = \Delta u/c_s$ is the Mach number. A correction factor w_c is defined so that $w_c = 0.4$ for $\mathcal{R} < 2 \times 10^5$ and $w_c = 0.2$ for

$\mathcal{R} > 2 \times 10^5$. The kinetic viscosity is given by $\nu = 0.353\sqrt{8/\pi}c_s l_g$ (Chapman & Cowling 1970), where $l_g = m_{\text{mol}}/(\sigma_{\text{mol}}\rho_g)$ is the mean free path. We set the mass and collision cross section of a gas molecule to $m_{\text{mol}} = 3.9 \times 10^{-27}$ kg and $\sigma_{\text{mol}} = 2.0 \times 10^{-19}$ m², respectively.

In the orbit calculation, we obtain the gas density ρ_g and the relative velocity between gas and dust particles $\Delta \mathbf{u}$ at the position of the particle from the results of hydrodynamic simulation, and calculate the gas drag force at each time step. We assume the gas surface density at Jupiter's orbit in the MMSN model (Hayashi 1981), $\Sigma_{g,0} = 1434$ kg m⁻², for the unperturbed region of the PPD.

While approaching the planet, sufficiently large particles undergo vertical oscillation across the midplane of the PPD due to the vertical component of the tidal force. In the case of the Epstein drag law, the critical radius $r_{d,\text{crit}}$ for this vertical oscillation can be expressed as $r_{d,\text{crit}} = v_{\text{th}}\rho_g/(2\rho_d\Omega_K)$, where $v_{\text{th}} = \sqrt{8/\pi}c_s$ is the thermal velocity of the gas. If we assume that the planet is located at 5.2 au from the central star in the MMSN model and the depletion factor of the gas surface density is given by f_H ($f_H = 1$ corresponds to the MMSN model), $v_{\text{th}} = 1.1 \times 10^3$ m s⁻¹, and $\Omega_K = 1.7 \times 10^{-8}$ rad s⁻¹, and the gas density at the midplane is $\rho_g = 1.5 \times 10^{-8}f_H$ kg m⁻³, thus we obtain $r_{d,\text{crit}} \simeq 0.5f_H$ m. For example, when a gap is opened around the planetary orbit and $f_H = 0.1$, we have $r_{d,\text{crit}} \simeq 5$ cm. We examined cases with $r_d = 10^{-4} - 10$ m, but we will mostly focus on the cases of $r_d = 10^{-4} - 10^{-2}$ m ($< r_{d,\text{crit}}$ when $f_H \gtrsim 0.02$), where the particles are easily coupled to the gas accreting into the CPD.

3.2.3 Settings of Orbital Integration for Solid Particles

We integrate Equation (3.1) using the eighth-order Runge-Kutta integrator as used in Homma et al. (2020). To focus on effects of the initial vertical distribution of particles, we assume that the particles are initially on circular orbits. This assumption is valid for the case of $r_d \leq r_{d,\text{crit}}$, because eccentricities of such small particles are quickly damped by gas drag (see Figure 11 in Homma et al. 2020). Then, the parameters that determine the initial conditions of particles are the impact parameter $b = a_s - a$ and the initial altitude z_0 , where a_s is the initial semi-major axis of the particle. We start orbital integration at the azimuthal boundary of the hydrodynamic simulation box; $x > 0$ and $y_0 = L_y/2 - L_y/n_y$ (Homma et al. 2020). Then, we derive the initial x -coordinate from the given impact parameter b and y_0 as $x_0 = \sqrt{b^2 - 8r_H^3/y_0}$ (Ida & Nakazawa 1989).

The conditions for the capture of particles and the termination of the orbital integration are the same as in Homma et al. (2020) (see also Tanigawa et al. 2014). Each particle is considered to be captured by the CPD when one of the following two conditions is met: (i) The orbit of an energetically captured particle becomes planet-centered and nearly circular in the CPD: $\tilde{E} < 0$, $e_p < 0.3$, $\tilde{a}_p < 0.5$, $|N_w| \geq 3$. Here $\tilde{E}$ is the energy integral given by

$$\tilde{E} = \frac{1}{2}(\dot{\tilde{x}}^2 + \dot{\tilde{y}}^2 + \dot{\tilde{z}}^2) - \frac{1}{2}(3\tilde{x}^2 - \tilde{z}^2) - \frac{3}{\tilde{r}} + \frac{9}{2}. \quad (3.6)$$

In the above, e_p and a_p are the eccentricity and semi-major axis of the planet-centered orbit

of the particle, respectively, and are given by (Murray & Dermott 1999):

$$\tilde{a}_p = \left(\frac{2}{\tilde{r}} - \frac{\tilde{v}_{\text{iner}}^2}{3} \right)^{-1}, \quad (3.7)$$

$$e_p = \sqrt{1 - \frac{j_{\text{iner}}^2}{3a_p}}, \quad (3.8)$$

where v_{iner} and j_{iner} are the velocity and the specific angular momentum around the planet in the inertial frame, respectively. N_w is the winding number around the planet (Iwasaki & Ohtsuki 2007). (ii) Even if the particle is not in a circular orbit around the planet, it is considered to be captured if it is captured energetically within the planet's Hill sphere and has orbited around the planet a sufficient number of times: $\tilde{E} < 0$, $\tilde{r} < 1$, $|N_w| \geq 15$.^{*1}

We terminate the orbital integration for each particle when any one of the above capture conditions (i) or (ii), or either of the following conditions is met: (iii) the particle collides with the planet: $r < r_p$, where r_p is the physical radius of the planet. We set $r_p = 10^{-3}r_H$ assuming the Jovian orbit (Ida & Nakazawa 1989, Ohtsuki 2012). (iv) The particle is far enough away from the planet: $r > y_0 + b + (2e_0 + i_0)a_0$, where e_0 , i_0 , and a_0 are the eccentricity, inclination, and semi-major axis of the particle's initial heliocentric orbit, respectively.

3.3 RESULTS

3.3.1 Examples of Particle Orbits

The orbital behavior of particles from the PPD to the CPD depends on their Stokes number St (Homma et al. 2020). Here we define St by the following equations using the planet-centered-Keplerian angular velocity Ω_p near the planet ($\tilde{r} < 0.5$) and star-centered-Keplerian angular velocity Ω_K elsewhere:

$$St \equiv \begin{cases} t_{\text{stop}}\Omega_p & (\text{for } \tilde{r} < 0.5), \\ t_{\text{stop}}\Omega_K & (\text{for } \tilde{r} \geq 0.5), \end{cases} \quad (3.9)$$

where the stopping time t_{stop} is described as

$$t_{\text{stop}} = m_d \Delta u / F_{\text{drag}} = \frac{8\rho_d r_d}{3C_D \rho_g \Delta u}. \quad (3.10)$$

Figure 3.1 shows examples of particle orbits and the change of the Stokes number along them in the case of $z_s = r_H$. In the case of $r_d = 10$ m (red), $St \gg 1$ and the effect of gas drag is sufficiently small, and the orbit is similar to that without gas drag (black). It oscillates in the vertical direction with the amplitude depending on the initial altitude and can be captured by the CPD when it happens to pass close to the planet.

In the cases of $0.1 \leq r_d \leq 1$ m (light blue and violet), $St \sim 1$ is maintained while approaching the Hill sphere. In the case of $r_d = 0.1$ m $\simeq r_{d,\text{crit}}$, $St = 0.5$ and the particle

^{*1}While we consider the capture of particles in both the prograde and retrograde directions, we find that all the particles captured in the prograde direction because the size of particles is sufficiently small and particles are dragged by the gas flow in the CPD.

gradually settles toward the mid-plane. When $St < 0.5$, particles cannot settle completely and approach the Hill sphere at an altitude slightly above the mid-plane and are captured from above by the CPD. On the other hand, when $St \gtrsim 0.5 - 1$, the vertical oscillation is not completely damped, and the particles approach the Hill sphere with a slight oscillation (see also Homma et al. 2020). The degree of oscillation damping depends on the density of the gas along the orbit, i.e., the depth of the gap formed around the planet's orbit. It should be noted that the gap depth obtained by our local simulation tends to be shallower than the one obtained by global simulation for the same planetary mass. Since the capture process for small particles with $St \lesssim 1$ are sensitive to the depth of the gap, it is important to take such effects into account when examining planetary-mass dependence (Maeda et al. 2022; see also § 3.4.5).

The particles with $r_d \leq 1$ cm (orange, green, and blue) have $St \ll 1$ and approach the Hill sphere while keeping a certain altitude, being more or less coupled to the gas flow. Then they move down nearly vertically with the accreting gas flow over the Hill sphere and become captured by the CPD.

Differences in the gas field around a planet due to differences in planetary mass affect particle orbits in the following ways: First, the impact parameter b of the accretion orbit is varied because of the structure of the accretion bands is modified (see § 3.3.2). Second, when the planetary mass is increased, the gas density around the planetary orbit tends to be reduced more due to gap opening, resulting in a larger Stokes number for the same particle size. This makes the particles with $St \simeq 1$ ($r_d = 10^{-1}$ m) more easily settled toward the midplane while approaching the planet.

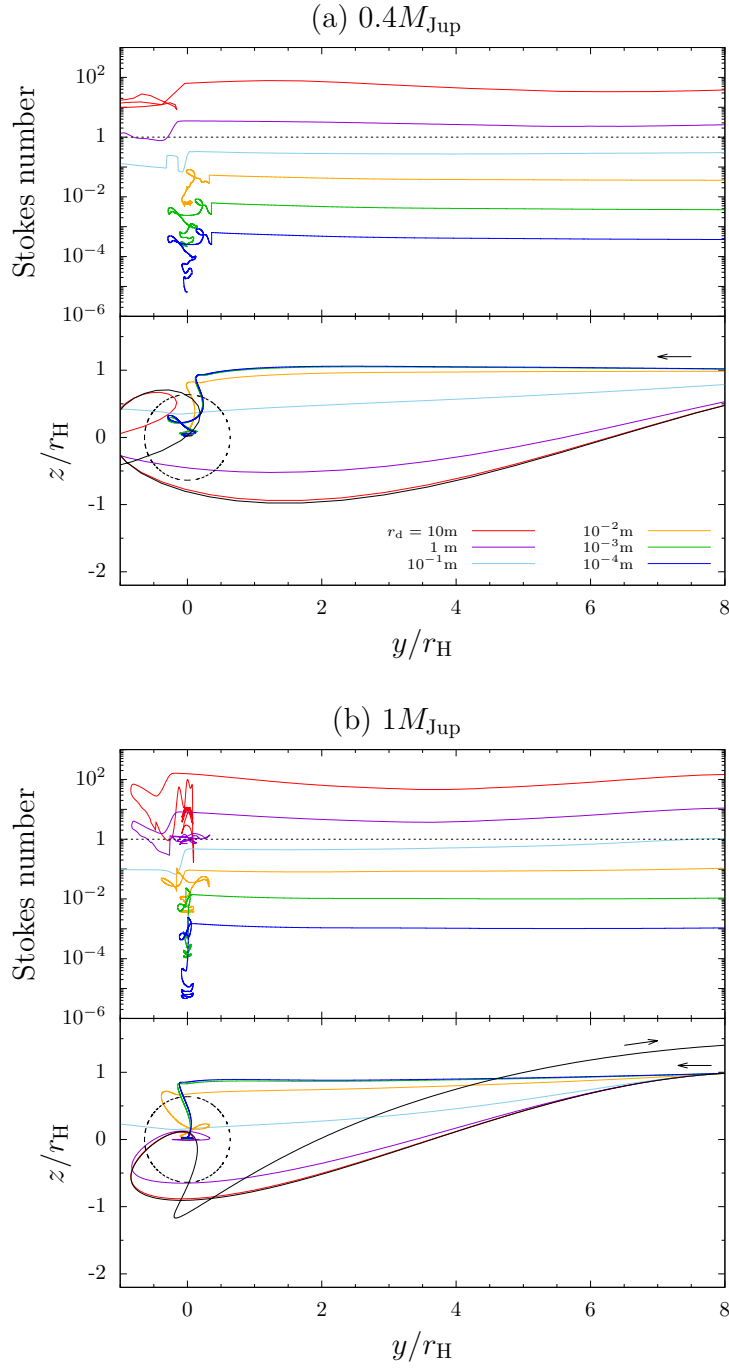


Figure 3.1: Examples of particle orbits and change of the Stokes number along the orbits in the case of $(\tilde{b}, \tilde{z}_s) = (2.3, 1.0)$ and $(2.4, 1.0)$ for $M_p = 0.4M_{\text{Jup}}$ (top panel) and $M_p = 1M_{\text{Jup}}$ (bottom panel), respectively. The colors show the size of particles; red, violet, light blue, orange, green, and blue correspond to $r_d = 10, 1, 0.1, 10^{-2}, 10^{-3}$, and 10^{-4} m, respectively. The black lines show the case without gas drag. The dashed lines in the bottom panels show the Hill sphere of the planet.

3.3.2 Initial Orbits of Captured Particles

In Figure 3.2, we show the distribution of the initial impact parameter b and initial altitude z_s of the particles captured by the CPD. The different colors mean the different sizes of the particles. The results for $r_d = 0.1$ cm (light blue) are shown as examples for the case of $St \sim 1$ for comparison with other cases of $St \ll 1$. In the case of the particles with $St \ll 1$ ($r_d \leq 10^{-2}$ m), the initial orbits of captured particles distribute above the midplane continuously in the z -direction in a zonal pattern except for $z_s \simeq 0$. Because particles of this size are greatly affected by the gas flow, the distribution of the dust accretion band is very similar to that of the gas accretion band (Tanigawa et al. 2012, Maeda et al. 2022). We confirm that sufficiently small particles initially near the midplane of the PPD cannot accrete into the CPD due to the radially outward gas flow near the midplane in the Hill sphere (Tanigawa et al. 2014, Homma et al. 2020, Maeda et al. 2022).

In the case of $St \ll 1$ ($r_d \leq 10^{-2}$ m), the radial width of the dust accretion band measured in units of r_H becomes wider with increasing planetary mass. For example, in the case of $r_d = 0.1$ mm (blue), while the width of the dust accretion band is $\Delta b_{\text{cap}} \lesssim 0.15 r_H$ for $M_p = 0.4 M_{\text{Jup}}$, $\Delta b_{\text{cap}} \gtrsim 0.3 r_H$ at maximum for $M_p = 1 M_{\text{Jup}}$. This expansion of Δb_{cap} is pronounced in the case of smaller particles. This is because the smaller particles are more affected by the gas flow and the width of the gas accretion band is wider for larger planetary masses (Maeda et al. 2022). In the case of $M_p = 1 M_{\text{Jup}}$, Δb_{cap} is larger at $z_s \gtrsim r_H$, which is attributed to the fact that the gas accretion band becomes slightly wider at $z \gtrsim r_H$ (see Fig.2.7 in Chapter 2 or Fig.7 in Maeda et al. 2022). Also, Δb_{cap} is almost independent of z_s when $r_d = 0.1$ m because the particles settle toward the midplane before they approach the planet. Thus, the range of b that leads to accretion is similar to that of $z_s \sim 0$, regardless of initial altitudes.

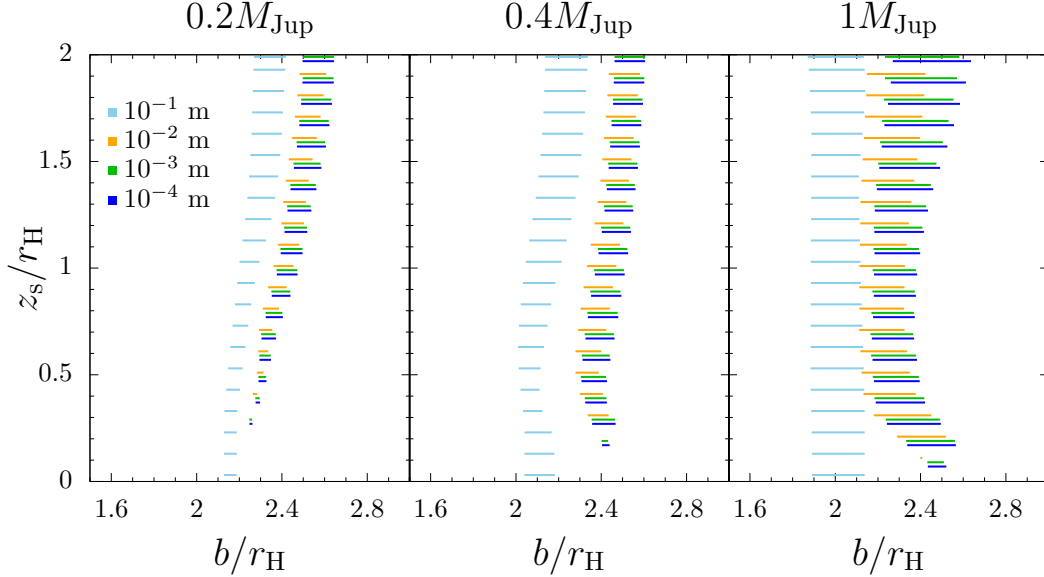


Figure 3.2: Distribution of the initial orbital parameters (b, z_s) of captured particles (dust accretion band). The colors show the size of the particle; light blue, orange, green, blue corresponds to $r_d = 0.1, 10^{-2}, 10^{-3},$ and 10^{-4} m, respectively. The vertical axis is plotted at every $z_s = 0.1 r_H$, but slightly shifted up and down to avoid overlapping of the lines.

3.3.3 Distribution of the Locations of Particles Capture in the CPD

Figure 3.3 shows the distribution of the coordinates (R, z) of particles when their capture conditions are met in the range $0 < z_s \leq r_H$ for the cases of two different sizes. We show the results for only two cases of $r_d = 10^{-2}$ m and 10^{-4} m. The results for $r_d = 10^{-3}$ m are similar to the case of $r_d = 10^{-4}$ m and are not shown here. In agreement with Homma et al. (2020), particles accreting with the gas are widely supplied onto the surface of the CPD. We found that the particles with $r_d = 10^{-4}$ m tend to be captured at more inner region of the CPD than those with 10^{-2} m. This suggests that small particles accreting from high altitudes can be delivered into more inner regions of the CPD with the gas (Homma et al. 2020). On the other hand, if particles in the PPD undergo significant settling in approaching the planet, they are captured in the midplane near the outer edge of the CPD. Although the size of the CPD is commonly $r_{\text{CPD}} \simeq 0.2r_H$ when $r_H/h_g \gtrsim 1$ (e.g., Figure 4 in Maeda et al. 2022), we found that the Hill-scaled radial positions of particle captured on the CPD are more widely distributed in the case of larger planets. This may reflect the fact that the size of the CPD measured in units of r_H and/or the gas density near the outer edge of the CPD is somewhat larger for a larger planetary mass (Figures 2.3 and 2.4; see also Figures 3 and 4 in Maeda et al. 2022).

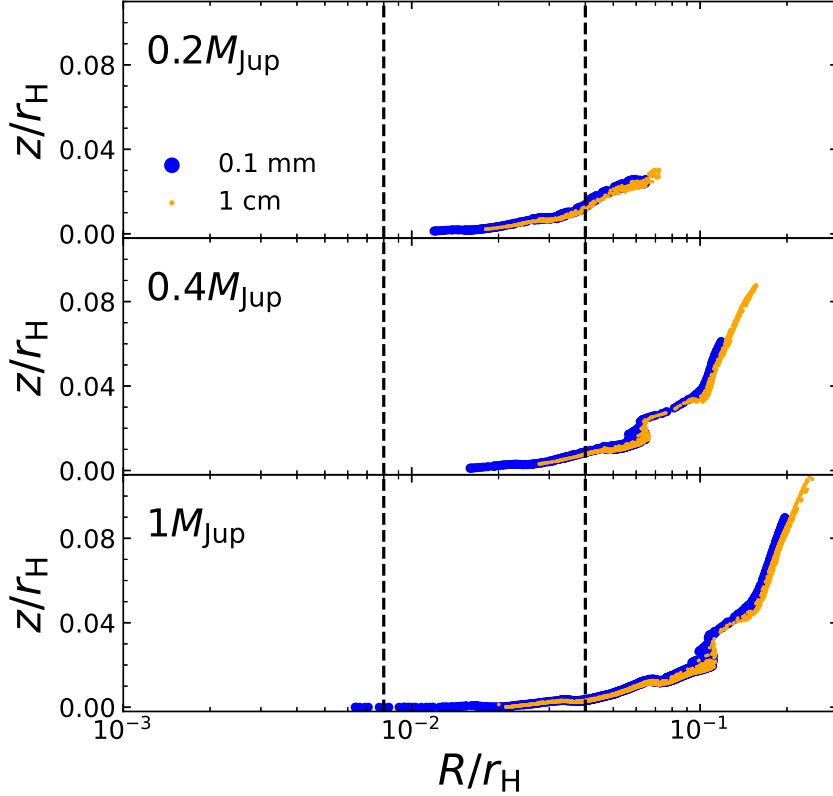


Figure 3.3: Radial and vertical positions (R, z) where the particle capture conditions are met for the case of $0 < z_s \leq r_H$. Orange and blue points represent results for $r_d = 10^{-2}$ m and 10^{-4} m, respectively. The two black vertical dashed lines show the current radial positions of Io and Callisto. The results for $r_d = 10^{-3}$ m are not shown here, but are similar to the case of $r_d = 10^{-4}$ m.

3.3.4 Capture Rate of Dust Particles onto the CPD

Next, we calculate the capture rates of particles onto the CPD. The capture rates in this work are obtained by counting the number of captured particles per unit time and unit surface number density of particles in the PPD, and P_{cap} is normalized by $r_H^2 \Omega_K$. For $r_d < r_{d,\text{crit}}$, the capture rate of particles which have initial altitude z_s is described by (Fujita et al. 2013, Tanigawa et al. 2014, Homma et al. 2020):

$$P_{\text{cap}}(r_d, z_s) = \int_{-\infty}^{\infty} \varphi_{\text{cap}}(r_d, z_s, \tilde{b}) \frac{3}{2} |\tilde{b}| d\tilde{b}, \quad (3.11)$$

where φ_{cap} is defined such that $\varphi_{\text{cap}} = 1$ for capture orbits and $\varphi_{\text{cap}} = 0$ otherwise. We adopted $d\tilde{b} = 5 \times 10^{-4}$ and performed calculations by varying z_s in increments of 0.1.

Figure 3.4 shows the capture rates for $r_d = 10^{-4}$ m. Although P_{cap} is non-dimensionalized by the Hill-scaling, the overall values of P_{cap} are larger for larger planetary masses, reflecting the increase in the width of the gas accretion band scaled by r_H (Figure 3.2). The

increase of P_{cap} at $z_s \gtrsim r_H$ for $M_p = 1M_{\text{Jup}}$ is attributed to the fact that the gas accretion band becomes slightly wider in this altitude range, as mentioned in § 3.3.2. We also found that $P_{\text{cap}} = 0$ at $z_s = 0$ for all the three cases, owing to the outward gas flow near the midplane in the Hill sphere (§ 3.3.2). The increase of the capture rate of dust with small z_s ($\lesssim 0.5r_H$) for $M_p = 1M_{\text{Jup}}$ can be explained by the extension of the gas accretion band to lower altitudes (Maeda et al. 2022).

Results for larger particle sizes are shown in Figure 3.5, with those for $r_d = 10^{-4}$ m with the dashed lines for comparison. We find that the results are quite similar for all the three particle sizes, because in almost all these cases dust particles have sufficiently small Stokes numbers and are coupled well with the gas. As an exception, a significant deviation from the other cases can be seen in the case of $r_d = 10^{-2}$ m at $z_s \gtrsim 1.5h_g$ when $M_p = 1M_{\text{Jup}}$. This is because the gas density is very low at such high altitudes ($z_s \gtrsim 2h_g$), so the Stokes number of the particles is large.

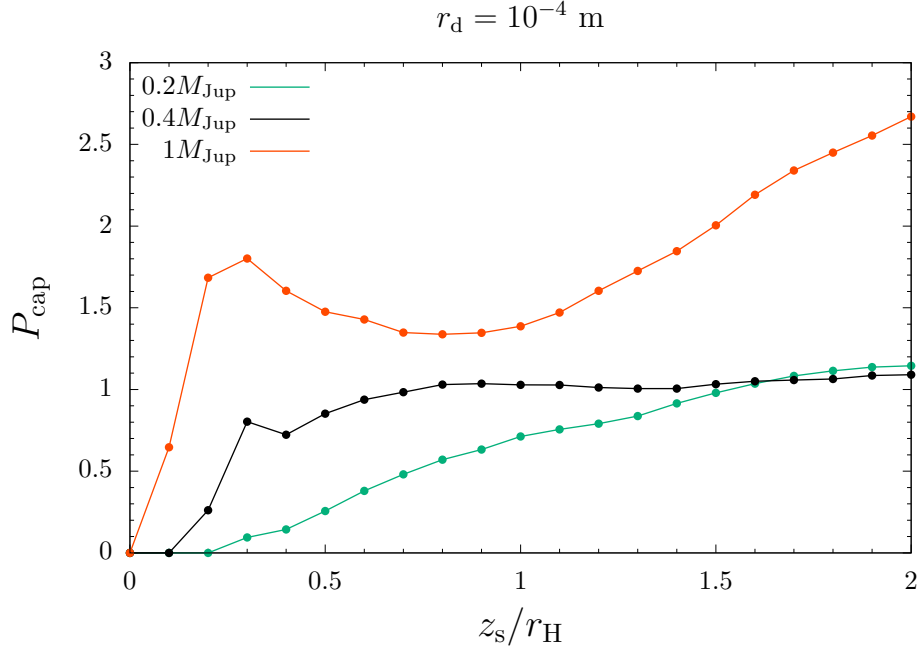


Figure 3.4: Capture rate P_{cap} as a function of the initial altitude z_s for $r_d = 10^{-4}$ m. The colors show the difference of the planetary mass; green, black, red correspond to $M_p = 0.2M_{\text{Jup}}$, $0.4M_{\text{Jup}}$, and $1M_{\text{Jup}}$, respectively.

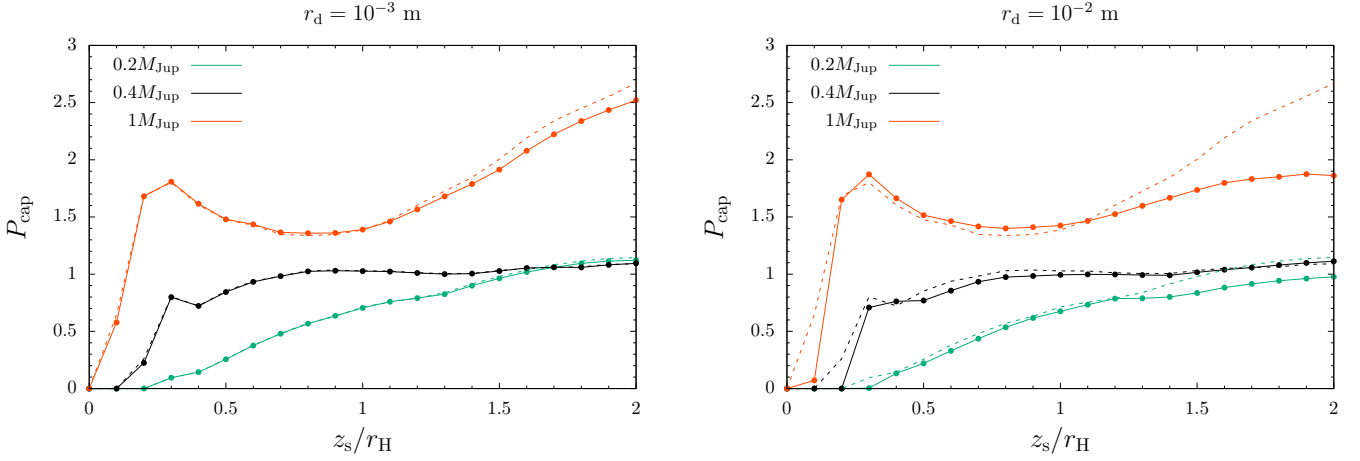


Figure 3.5: Same as Figure 3.4 but for $r_d = 10^{-3}$ m (left panel) and 10^{-2} m (right panel), respectively. The dashed line shows the results for $r_d = 10^{-4}$ m for comparison.

3.4 DISCUSSIONS

3.4.1 Capture Rates of Vertically Stirred Dust Particles

Integrating the capture rates per unit surface number density of particles in the PPD (i.e., $P_{\text{cap}}(r_d, z_s)$ given by Equation (3.11)) over z_s with a given vertical distribution of particles, we can calculate the total capture rates of particles into the CPD. The degree of vertical stirring of dust particles in the PPD can be expressed by the dust scale height h_d . Homma et al. (2020) considered dust stirring due to turbulence and used the dust scale height h_d expressed in terms of the turbulent viscosity parameter α (Shakura & Sunyaev 1973) and the Stokes number of particles St (Youdin & Lithwick 2007). Then they obtained total capture rates and mass accretion rates of dust particles for several combinations of α and St . However, turbulence is not the only mechanism that stirs up dust particles in the PPD. For example, recent studies show that the meridional circulation caused by an embedded planet can stir up dust particles (Bi et al. 2021, Szulágyi et al. 2022).

Therefore, rather than focusing on any specific mechanism for dust particle stirring, in the present work we will obtain the total capture rate $P_{\text{cap,total}}$, treating the dust scale height h_d as a parameter. We assume that the vertical distribution of particles is given by the Gaussian distribution with a scale height h_d ;

$$n(h_d, z_s) = \frac{\Sigma_d}{\sqrt{2\pi}h_d m_d} \exp\left(-\frac{z_s^2}{2h_d^2}\right). \quad (3.12)$$

Then the total capture rate of particles $P_{\text{cap,total}}$ with this vertical distribution is given by

$$P_{\text{cap,total}}(h_d) = \frac{\int_{-\infty}^{\infty} P_{\text{cap}}(z_s) n(h_d, z_s) dz_s}{\int_{-\infty}^{\infty} n(h_d, z_s) dz_s}. \quad (3.13)$$

Figure 3.6 shows the plots of $P_{\text{cap,total}}(h_d)$. The behavior of $P_{\text{cap,total}}(h_d)$ can be roughly explained by the z_s -dependence of the width of the dust accretion band (Figure 3.2), i.e., the total capture rate is larger for a larger planetary mass and a larger dust scale height.

Bi et al. (2021) investigated effects of planet-driven meridional circulation on vertical stirring of dust using a three-dimensional hydrodynamic simulation considering the back-reaction of dust on the gas. They showed that even in the case of a planet with a Saturnian mass ($M_p \simeq 0.3M_{\text{Jup}}$), dust particles are easily stirred up to $h_d \simeq 0.6h_g$. In the case of $h_d = 0.6h_g$ in Figure 3.6, we find that $P_{\text{cap,total}} \simeq 0.4$ for $M_p = 0.2M_{\text{Jup}}$, $\simeq 0.6$ for $M_p = 0.4M_{\text{Jup}}$, and $\simeq 1.2$ for $M_p = 1M_{\text{Jup}}$, respectively. That is, although $P_{\text{cap,total}}$ is normalized by $r_H^2 \Omega_K$ as mentioned above, its value for $M_p = 1M_{\text{Jup}}$ is about three times larger than for $M_p = 0.2M_{\text{Jup}}$ as compared to the simple Hill-scaling. As for the dependence on particle size in the size range considered here (0.1 mm — 1 cm), the total capture rate is roughly determined by the dust scale height and the planetary mass, suggesting that the particle size dependence is not significant. However, since the dust scale height likely depends on the particle size (or the Stokes number), the total capture rate likely depends on the dust size via the dust scale height.

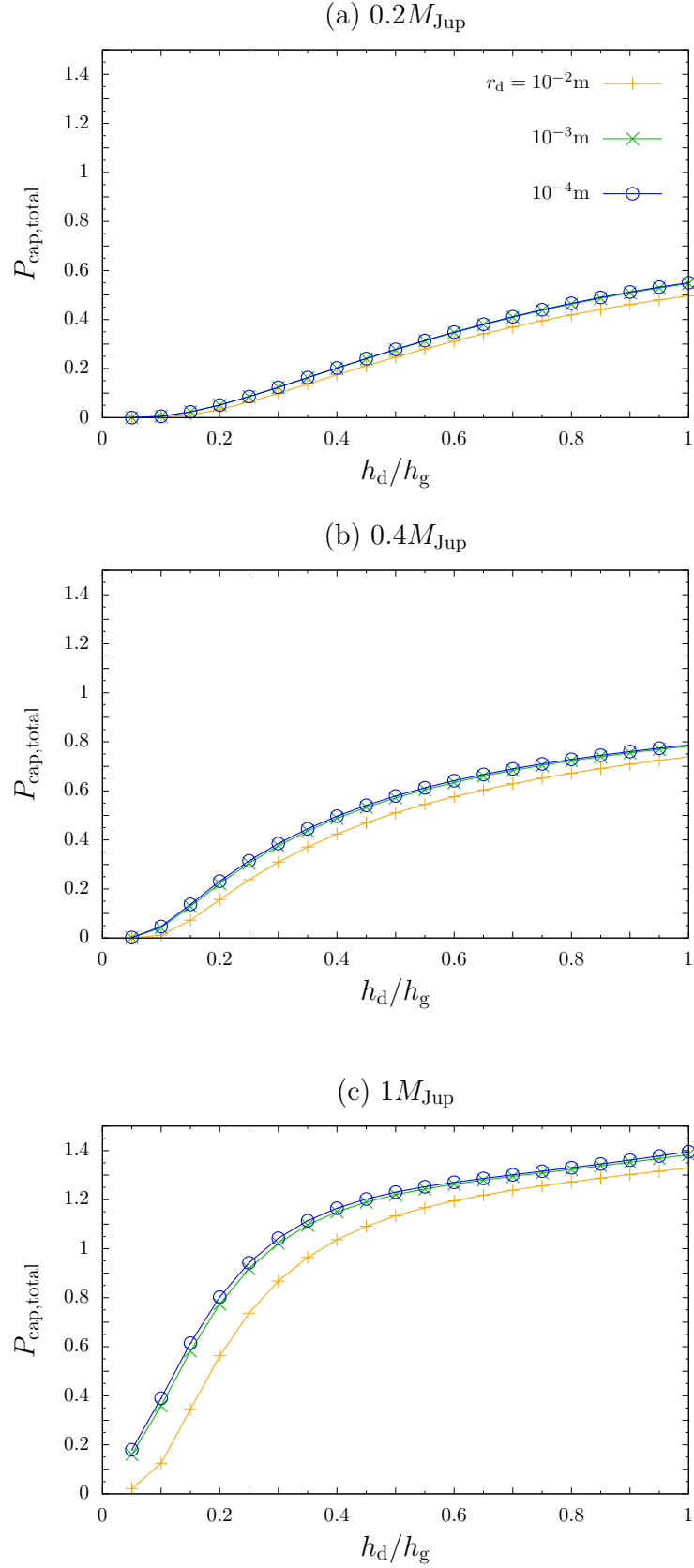


Figure 3.6: Total capture rate $P_{\text{cap,total}}$ as a function of h_d/h_g . Top, middle, and bottom panels show the results for $M_p = 0.2, 0.4$, and $1 M_{\text{Jup}}$, respectively. Colors show the dust size, and orange, green, and blue correspond to $r_d = 10^{-2}, 10^{-3}$, and 10^{-4} m , respectively.

3.4.2 Degree of Dust Retention in Accreting Gas

Recent theoretical models of satellite formation in the CPD suggest that one of the key parameters for the formation of satellitoids and satellites in the CPD is the ratio of dust-to-gas inflow rates (Shibaike et al. 2017, 2019). Using $P_{\text{cap,total}}$ we obtained above, we can derive the mass accretion rate of dust into the CPD from (Homma et al. 2020)

$$\dot{M}_d = \Sigma_d r_H^2 \Omega_K P_{\text{cap,total}}, \quad (3.14)$$

where Σ_d is the dust surface density at the position of the dust accretion band.

Now, following Maeda et al. (2022), we consider the gas flowing through the area of the accretion band at $(x, y) = (x_{g,\text{ab}}, L_y/2)$, where $x_{g,\text{ab}}$ is a typical value of the x -coordinate of the accretion band. The velocity of the gas passing through the area of the accretion band is $(3/2)x_{g,\text{ab}}\Omega_K$ in the coordinate system rotating with the planet. Then, the mass accretion rate of the gas into the CPD is expressed as:

$$\dot{M}_g = D_g \Sigma_g, \quad (3.15)$$

$$D_g = 2 \times \frac{3}{2} x_{g,\text{ab}} \Omega_K \bar{w}_g, \quad (3.16)$$

where D_g is the *accretion area* of the gas (Tanigawa & Tanaka 2016). We obtain $\bar{w}_g$ by averaging the width of the accretion band $w_g(z)$ over z with the gas density distribution (Maeda et al. 2022):

$$\bar{w}_g = \frac{\int_0^{z_{\text{max}}} w_g(z) \exp\left(-\frac{z^2}{2h_g^2}\right) dz}{\int_0^{z_{\text{max}}} \exp\left(-\frac{z^2}{2h_g^2}\right) dz}. \quad (3.17)$$

Similarly, the dust accretion rate into the CPD can be obtained using the accretion area of the dust particles D_d and the averaged width of the dust accretion band $\bar{w}_d$ as

$$\dot{M}_d = D_d \Sigma_d, \quad (3.18)$$

$$D_d = 2 \times \frac{3}{2} x_{d,\text{ab}} \Omega_K \bar{w}_d, \quad (3.19)$$

$$\bar{w}_d = \frac{\int_0^{z_{\text{max}}} w_d(z) \exp\left(-\frac{z^2}{2h_d^2}\right) dz}{\int_0^{z_{\text{max}}} \exp\left(-\frac{z^2}{2h_d^2}\right) dz}. \quad (3.20)$$

Then the ratio of dust-to-gas inflow rates χ is given by

$$\chi = \frac{\dot{M}_d}{\dot{M}_g} = \frac{D_d \Sigma_d}{D_g \Sigma_g}. \quad (3.21)$$

In the limit of a very small dust size, dust particles are completely coupled to the gas and we have $h_d = h_g$ and $\bar{w}_d = \bar{w}_g$, thus $D_d = D_g$. In this case, we obtain $\chi = \Sigma_d/\Sigma_g$, i.e., the ratio of dust-to-gas inflow rates is determined by the ratio of dust-to-gas surface density at the accretion band (feeding zone). On the other hand, if the dust-gas coupling is not perfect, $h_d < h_g$ due to dust settling, and dust is depleted in the gas accreting onto the CPD, resulting in $D_d/D_g < 1$ (Tanigawa et al. 2012). Here, we call D_d/D_g as *degree of dust retention* of accreting gas into the CPD.

The surface densities of dust and gas at the accretion band depend on the depth and width of the gap in the PPD, which depends on various parameters, such as the viscosity of the PPD. In order to avoid uncertainty related to such uncertain parameters, we will focus on the degree of dust retention D_d/D_g to examine the planetary mass dependence of the ratio of dust-to-gas inflow rates in the accretion band. For the range of planetary masses considered in this study corresponding to $0.8 \leq r_H/h_g \leq 1.36$, the width of the gas accretion band is approximately given by (Equation (2.15); see also Maeda et al. 2022)

$$\frac{\bar{w}_g}{h_g} = 0.12 \left(\frac{r_H}{h_g} \right)^3. \quad (3.22)$$

Substituting Equation (3.22) into Equation (3.16) and setting $x_{g,ab} = 2.2r_H$, we obtain

$$D_g = 0.79 r_H^4 h_g^{-2} \Omega_K. \quad (3.23)$$

As for the accretion of dust, from Equations (3.14) and (3.18), we obtain

$$D_d = P_{\text{cap,total}} r_H^2 \Omega_K. \quad (3.24)$$

From Equations (3.23) and (3.24), we can obtain the degree of dust retention of accreting gas into the CPD as

$$\frac{D_d}{D_g} = 1.26 P_{\text{cap,total}} \left(\frac{r_H}{h_g} \right)^{-2}, \quad (3.25)$$

where $P_{\text{cap,total}}$ can be obtained from our numerical results.

Figure 3.7 shows the plots of D_d/D_g obtained from Equation (3.25). We confirm that $D_d/D_g \simeq 1$ when dust particles are perfectly coupled to the gas and $h_d/h_g \simeq 1$, while D_d/D_g decreases with decreasing dust scale height due to insufficient dust stirring in the PPD. The decrease in D_d/D_g at small dust scale heights is more pronounced for smaller planetary masses, because the accretion band of dust and gas becomes narrower at low altitudes for small planetary masses (Figure 3.2). On the other hand, for $r_H/h_g = 1.36$ ($M_p = 1M_{\text{Jup}}$), $D_d/D_g \gtrsim 0.1$ even when $h_d/h_g = 0.1$.

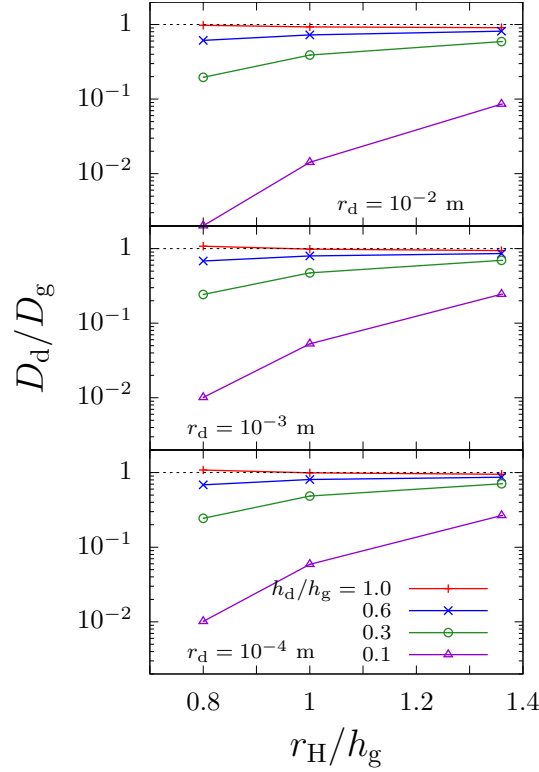


Figure 3.7: Degree of dust retention of accreting gas into the CPD as a function of r_H/h_g . The top, middle, bottom panels show the case of $r_d = 10^{-2}$, 10^{-3} , and 10^{-4} m, respectively. Color means the dust scale height in the PPD; violet, green, blue, and red correspond to $h_d/h_g = 0.1$, 0.3 , 0.6 , and 1.0 , respectively.

When the surface densities of dust and gas at the accretion band are given, we can determine the ratio of dust-to-gas inflow rates into the CPD combining them with the degree of dust retention D_d/D_g obtained above. The ratio of surface densities of dust and gas at the accretion band depends on the depth and width of gap opened by the planet and the radial position of the accretion band relative to the gap. As an example, in § 3.4.3, we derive dust mass accretion rates onto the CPD and the ratio of dust-to-gas inflow rates in the case where the surface densities of dust and gas at the accretion band are given using simple models based on results of global hydrodynamic simulation.

The surface density of dust at the accretion band depends on dust size. Particles with $St \sim 1$ are easily trapped at the pressure bump of the gap edge and the surface density becomes high (Zhu et al. 2012, Weber et al. 2018), and even planetesimals may form there (Eriksson et al. 2020, Shibaike & Alibert 2020, 2023). Then collision and fragmentation of the planetesimals at the pressure bump can provide a significant amount of dust, which can diffuse into the gap (Kobayashi et al. 2012, Stammerl et al. 2023). While recent studies using hydrodynamic simulations including gas and dust components obtain empirical formulae for the depth and width of the dust gap (Zhang et al. 2018), detailed studies of dynamical behavior of dust and gas around the gap is still in progress. Further investigation of the surface density distribution of dust and gas around the planetary orbit will be important to obtain the ratio of dust-to-gas inflow rates into the CPD and derive constraints on satellite

formation.

3.4.3 Applications

Dust Mass Accretion Rates

In order to obtain dust mass accretion rates onto the CPD using Equation (3.14) with our numerical results for $P_{\text{cap,total}}$, we need to assume the dust surface density in the accretion band. Here, we derive dust mass accretion rates using the surface density at the bottom of the gap.

Zhang et al. (2018) performed two-dimensional two-fluid hydrodynamic simulations for dust and gas, and obtained empirical formulae for the width and depth of the dust gap. The formulae obtained for the depth of the dust gap is

$$\frac{\Sigma_{\text{d,gap}}}{\Sigma_{\text{d,peak}}} = \frac{1}{1 + CK^D}, \quad (3.26)$$

$$\frac{K}{24} = \frac{M_{\text{p}}/M_{\text{c}}}{0.001} \left(\frac{h_{\text{g}}/a}{0.07} \right)^{-2.81} \left(\frac{\alpha}{10^{-3}} \right)^{-0.38}, \quad (3.27)$$

where $\Sigma_{\text{d,gap}}$ and $\Sigma_{\text{d,peak}}$ are the bottom and peak values of the dust surface density distribution, respectively. The values of the fitting parameters C and D for various values of the Stokes number of the dust particles are obtained from the hydrodynamic simulations (see Table 2 in Zhang et al. 2018). We assume α , the efficiency of the viscous angular momentum transport outside the gap, is independent of the dust vertical diffusion.

Figure 3.8 shows the relationships between the depth of the dust gap and $r_{\text{H}}/h_{\text{g}}$. We find that the dust gap becomes deeper with increasing planetary mass and increasing dust size.

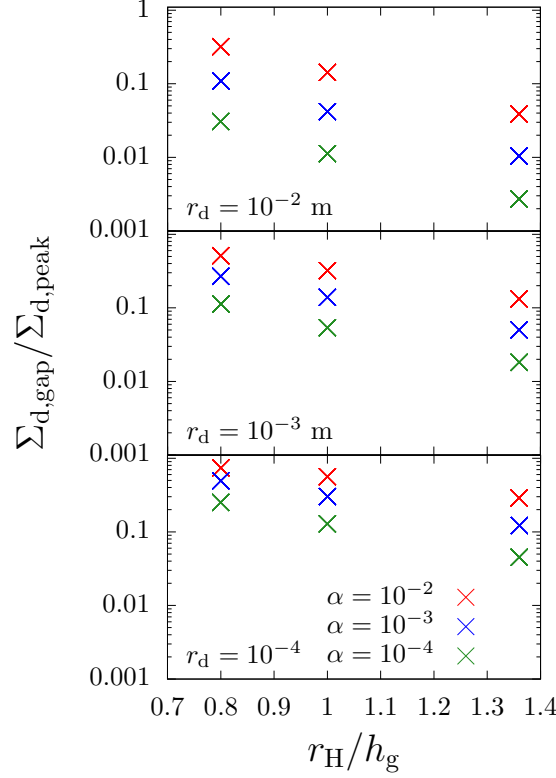


Figure 3.8: Relationship between the depth of dust gap and r_H/h_g obtained by the empirical formulae of Zhang et al. (2018). Colors represent results for different values of the viscous parameter of the PPD α : red, blue, and green correspond to $\alpha = 10^{-2}$, 10^{-3} , and 10^{-4} , respectively. Top, middle, and bottom panels show the cases of $r_d = 10^{-2}$, 10^{-3} , and 10^{-4} m, respectively.

Now, we obtain the dust mass accretion rate onto the CPD from Equation (3.14). We assume that the dust surface density at the accretion band is equal to the value at the bottom of the dust gap. Then,

$$\Sigma_d = \Sigma_{d,\text{gap}} = \frac{\Sigma_{d,\text{gap}}}{\Sigma_{d,\text{peak}}} f_{\text{peak}} \Sigma_{d,0} \quad (3.28)$$

$$f_{\text{peak}} \equiv \frac{\Sigma_{d,\text{peak}}}{\Sigma_{d,0}}, \quad (3.29)$$

where $\Sigma_{d,0}$ is the dust surface density at the unperturbed region of the PPD, and $\Sigma_{d,\text{gap}}/\Sigma_{d,\text{peak}}$ is obtained using Equation (3.26). Since the dust particles treated in this study are sufficiently small to avoid significant accumulation at the gas pressure bump, we assume $f_{\text{peak}} = 1$.

Figure 3.9 shows the plots of the dust mass accretion rates as a function of h_d/h_g for various values of planetary mass, particle size, and the viscosity parameter α of the PPD. We find that the mass accretion rate and its dependence on dust scale height are nearly independent of the planetary mass for $r_d = 10^{-2}$ m. As we mentioned in § 3.4.1, $P_{\text{total,cap}}$ in the case of strong vertical stirring of particles (i.e., $h_d/h_g \simeq 1$) becomes about three times larger when the planetary mass increases from $0.2M_{\text{Jup}}$ to $1M_{\text{Jup}}$ (Figure 3.6). In

this case, the planet's Hill radius increases by about a factor of 1.7, from $r_H/h_g = 0.8$ to 1.36, thus r_H^2 in Equation (3.14) increases by a factor of $(1.7)^2 \sim 3$. On the other hand, from the upper panel of Figure 3.8, $\Sigma_{d,\text{gap}}$ in the case of $r_d = 10^{-2}$ m becomes about one order of magnitude smaller when the planetary mass increases from $0.2M_{\text{Jup}}$ ($r_H/h_g=0.8$) to $1M_{\text{Jup}}$ ($r_H/h_g=1.36$). As a result, the effects of increased planetary mass on the above three quantities that appear on the r.h.s. of Equation (3.14) nearly cancel out, resulting in the mass accretion rate that is nearly independent of the planetary mass in the case of $r_d = 10^{-2}$ m. On the other hand, in the case of $r_d = 10^{-4}$ m, the change of $\Sigma_{d,\text{gap}}$ due to the increase in the planetary mass is small, so the effects of increased $P_{\text{total,cap}}$ and r_H with increased planetary mass are dominant. Therefore, the mass accretion rate significantly increases with increasing planetary mass in this case. In all the cases shown in Figure 3.9, mass accretion rates are larger for smaller particles due to the shallower gap opening for smaller particles (i.e., $\Sigma_{d,\text{gap}}$ becomes larger, as shown in Figure 3.8).

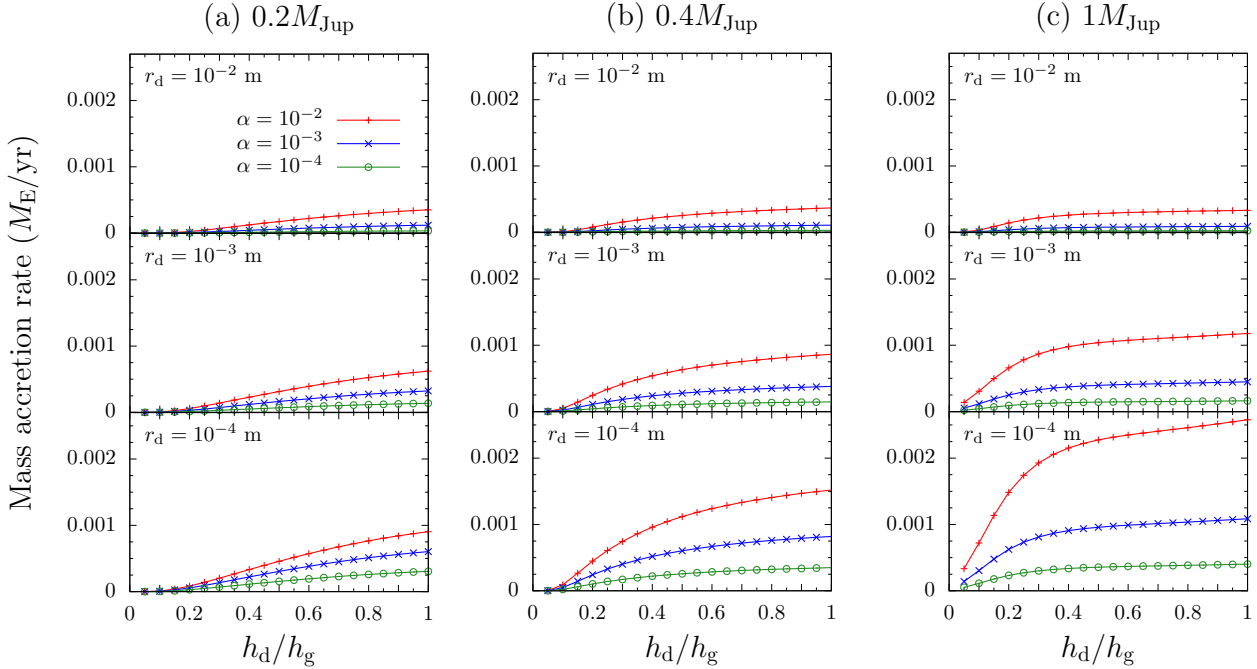


Figure 3.9: Dust mass accretion rate onto the CPD as a function of the dust scale height h_d , where the effects of dust gap is taken into account. Colors represent the results for different values of the viscous parameter of the PPD α : red, blue, and green correspond to $\alpha = 10^{-2}$, 10^{-3} , and 10^{-4} , respectively. Top, middle, and bottom panels show the cases of $r_d = 10^{-2}$, 10^{-3} , and 10^{-4} m, respectively.

Ratio of Dust-to-Gas Inflow Rates

Using the results of this work together with the empirical formulae of the surface densities of gas and dust at the gap bottom (Kanagawa et al. 2015, Zhang et al. 2018), we obtain the ratio of dust-to-gas inflow rates onto the CPD. Using the total capture rate $P_{\text{cap,total}}$ obtained in the present work and the gas mass accretion rate $\dot{M}_g$ obtained by the hydrodynamic simulation of Maeda et al. (2022) (see Chapter 2), the ratio of dust-to-gas inflow rates is obtained by

the following equation (Homma et al. 2020):

$$\chi = \frac{\dot{M}_d}{\dot{M}_g} = \frac{P_{\text{cap,total}} \Sigma_d h_g}{\tilde{M}'_g \Sigma_{g,0} r_H}, \quad (3.30)$$

where we substituted the dust surface density at the dust gap obtained by Equation (3.26) into Σ_d . In the above, $\tilde{M}'_g$ is the corrected gas surface density at the gap using the empirical formulae obtained by the global hydrodynamic simulation (Kanagawa et al. 2015; see also Maeda et al. 2022), which is obtained as

$$\tilde{M}'_g = \tilde{M}_g \times \frac{\Sigma_{g,\text{glo}}}{\Sigma_{g,\text{loc}}}, \quad (3.31)$$

where $\Sigma_{g,\text{glo}}$ and $\Sigma_{g,\text{loc}}$ are the gas surface densities at the gap bottom obtained by the global simulation of Kanagawa et al. (2015) and the local simulation of Maeda et al. (2022) (Chapter 2), respectively.

Figure 3.10 shows the ratio of dust-to-gas inflow rates as a function of M_p/M_{Jup} . In the case of small dust scale height ($h_d/h_g \lesssim 0.1$), the ratio of dust-to-gas inflow rates increases with increasing planetary mass. For example, in the case of $h_d/h_g = 0.1$ and $\alpha = 10^{-2}$, the ratio of dust-to-gas inflow rates increases by about one order of magnitude when the planetary mass increases from $0.2M_{\text{Jup}}$ ($r/h_g = 0.8$) to $1M_{\text{Jup}}$ ($r/h_g = 1.36$). This reflects the fact that the dust accretion band extends down to lower altitudes for a large planetary mass (§ 3.4.2), which significantly influences the dust accretion rates when the vertical stirring of dust particles is limited. On the other hand, for the larger dust scale height ($h_d/h_g \gtrsim 0.3$), the ratio of dust-to-gas inflow rates is nearly independent of planetary mass or even decreases with increasing planetary mass. In this case, the effect of the deeper gap (thus lower dust surface density) for a larger planetary mass is dominant. Thus, the planetary mass dependence of the ratio of dust-to-gas inflow rates into the CPD varies depending on the degree of vertical stirring of dust particles in the PPD.

Implication for Satellite Formation Models

Shibaike et al. (2017) investigated satellitesimal formation by calculating collisional growth of dust in a one-dimensional steady CPD. They found that satellitesimals can be formed if the ratio of dust-to-gas inflow rates is $\chi \simeq 1$. On the other hand, in the case of smaller χ , they found that particles that have grown from small sizes with $St \ll 1$ to larger sizes with $St \simeq 1$ quickly fall to the central planet and cannot form satellitesimals. Figure 3.10 shows that $\chi \lesssim 10^{-2}$ even when the PPD viscosity parameter is as high as $\alpha = 10^{-2}$ and the dust scale height is sufficiently large, indicating that the conditions for the formation of satellitesimals in Shibaike et al. (2017) cannot be satisfied. Recently, Shibaike & Mori (2023) investigated the satellitesimal formation in the CPD with magnetic wind-driven accretion and found that such CPDs can relax the condition for satellitesimal formation ($\chi \geq 0.02$). However, even this relaxed condition seems difficult to satisfy in our results shown in Figure 3.10.

On the other hand, Shibaike et al. (2019) proposed a scenario of Galilean satellite formation, called “slow-pebble-accretion scenario”, which can reproduce major characteristics of the current Galilean satellite systems, such as their orbits, masses, and compositions. In this scenario, several planetesimals captured by the CPD grow by accretion of pebbles that

are continuously supplied to the CPD, while they slowly move inward in the CPD to form satellites. They assumed that the ratio of dust-to-gas inflow rates is $\chi = 0.0026$, independent of the stages of the growth of the host planet. We plotted the value of χ ($= 0.0026$) that corresponds to the one assumed in Shibaïke et al. (2019) with the dashed lines in Figure 3.10. Figure 3.10 shows that the value of χ assumed in Shibaïke et al. (2019) can be achieved in cases where α is large and/or the dust scale height is large, although the values of χ that we obtained vary somewhat depending on adopted dust size and planetary mass.

According to the polarization observation of HD 163296 by ALMA, the dust scale height in the gap is estimated to $h_d = 0.3 - 0.7h_g$ and the dust size is $r_d \lesssim 10^{-4}$ m (Ohashi & Kataoka 2019). From our results, the condition for satellitesimal formation obtained by Shibaïke et al. (2019) can be achieved in cases where $\alpha \sim 10^{-2}$. Cilibrasi et al. (2018) performed a population synthesis simulation of satellite formation around a Jupiter-mass planet using the results of radiative hydrodynamical simulation obtained by Szulágyi et al. (2017). In their model, dust particles inflow onto the CPD with the same profile as the gas with the ratio of dust-to-gas inflow rates (0.03 – 0.5), and the satelliteseimals were assumed to grow via streaming instability. Figure 3.10 shows that such high ratio of dust-to-gas inflow rates ($\sim 10^{-2} - 10^{-1}$) can only be achieved under limited conditions of $\alpha \gtrsim 10^{-2}$, $h_d/h_g \simeq 1$, and $M_p \simeq 0.2M_{\text{Jup}}$. However, it has recently been shown that planet-driven meridional circulation could increase the ratio of dust-to-gas inflow rates to $\sim 10^{-2} - 10^{-1}$ (Szulágyi et al. 2022). These conditions of high ratio of dust-to-gas inflow rates could be achieved by considering global flows in the PPD.

Bae et al. (2022) estimated the dust-to-gas mass ratio of the CPD candidate of AS 209b as $\lesssim 2 \times 10^{-4} - 9 \times 10^{-4}$, suggesting that the dust in the CPD is more depleted than the typical ISM environment. They inferred that the depletion is presumably due to limited supply and/or rapid radial drift of dust within the CPD. Our results support the former, although we cannot rule out the possibility of the latter. It should be noted that the results presented here depend on the assumed dust/gas surface densities, which are described in § 3.4.3.

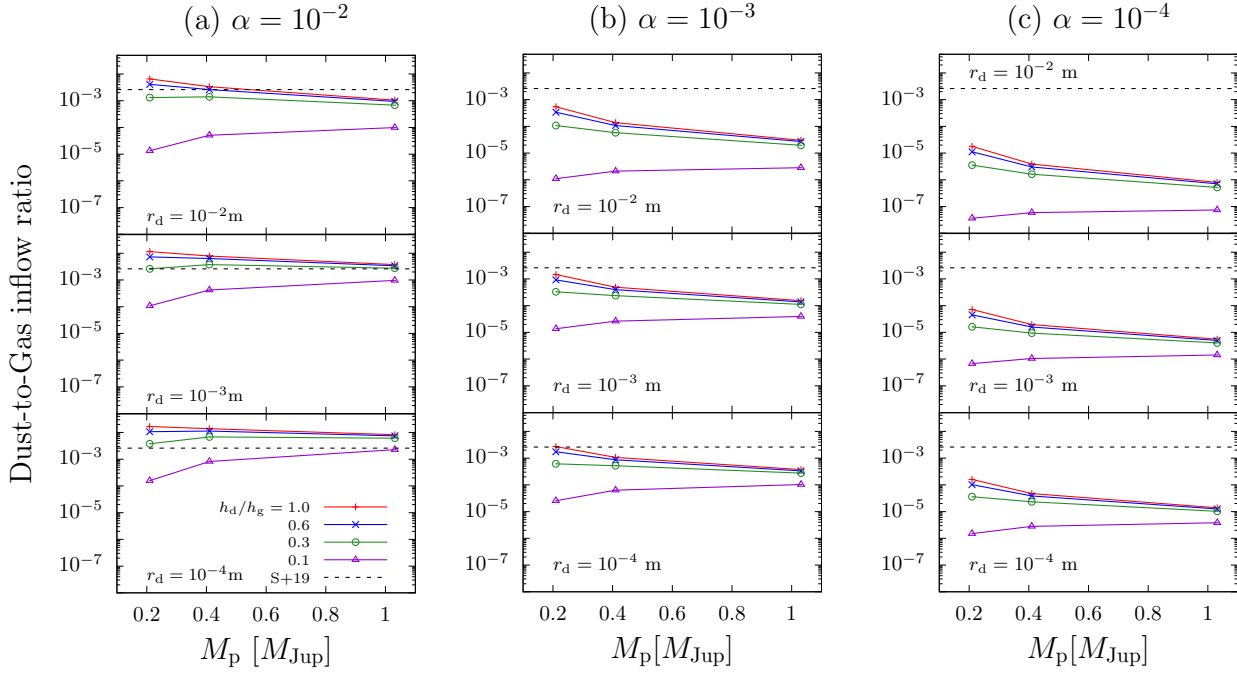


Figure 3.10: Ratio of dust-to-gas inflow rates onto the CPD as a function of r_H/h_g . Different colors represent different dust scale heights in the PPD: red, blue, green, and violet correspond to $h_d/h_g = 1.0, 0.6, 0.3$, and 0.1 , respectively. The dashed line corresponds to the value assumed in the Galilean satellite formation model of Shibaie et al. (2019), $\chi = 0.0026$.

3.4.4 Capture Position of Dust Particles Compared to Planetesimals

In § 3.3.3, we examined the distribution of the capture positions of dust particles in the CPD (Figure 3.3). Fujita et al. (2013) examined capture of planetesimals by the CPD and obtained the critical radial distance from the planet for capture, i.e., those planetesimals passing within this critical radius are captured due to strong gas drag. Suetsugu & Ohtsuki (2017) also examined orbital evolution of captured planetesimals in the CPD. These studies showed that meter- to kilometer-sized planetesimals can be captured in the region with $R \lesssim 10^{-2}r_H$ for the gas-starved CPD, which roughly includes the current radial locations of the Galilean satellites and extends to more inner regions than the dust capture locations shown in Figure 3.3. This is because planetesimals need sufficient energy dissipation to be captured by the CPD, which requires high gas density. It should be noted that the capture radius as well as the maximum size of planetesimals that can be captured depend on the surface density of the CPD, and larger planetesimals can be captured in more outer regions if the CPD is more massive (Ronnet et al. 2018). Also, Ronnet & Johansen (2020) showed that most planetesimals that are captured by the CPD are strongly ablated due to frictional heating, resulting in the supply of dust grains to the CPD. They also showed that planetesimals smaller than 10 km would be ablated mainly at $R \gtrsim 10^{-2}r_H$. These results suggests that the dust particles are supplied to the CPD mainly at the regions with $R \gtrsim 10^{-2}r_H$.

3.4.5 Model Limitations

In the present work, we investigated delivery of dust particles from the PPD to the CPD by performing orbital integration of dust particles under the influence of the gas flows in the vicinity of a planet obtained by high-resolution local hydrodynamic simulation, but some simplifications were introduced. First, the local hydrodynamic simulation allows us to investigate the gas flow near the planet with high resolution, but as mentioned earlier, it is difficult to accurately represent the gap structures. We used the assumption of the surface densities of gas and dust based on the gap model derived from global simulation (Kanagawa et al. 2015, Zhang et al. 2018) to estimate the mass accretion rates of gas (Chapter 2; see also Maeda et al. 2022) and dust (§ 3.4.3), and the ratio of dust-to-gas inflow rates (§ 3.4.3). However, direct use of global simulation is desirable to obtain realistic gap structures for both gas and dust simultaneously. Second, in our simulation, the gas is assumed to be isothermal and inviscid for simplicity, and radiative transport is not included. In addition, despite the assumption that the gas flow is laminar in the unperturbed state, we assume that dust particles are vertically stirred by some mechanism in the PPD. We treated the degree of vertical stirring as a parameter using the dust scale height, which is assumed to be independent of the efficiency of the angular momentum transport of the PPD. Furthermore, although the influence of the gas flow on the orbital motion of dust particles is taken into account, the back reaction that dust exerts on the gas is not considered.

Recently, treating these effects more realistically, global simulations of PPDs with gas-dust two-component fluids have been performed (e.g., Binkert et al. 2021, Szulágyi et al. 2022). The mechanisms that can stir up dust particles have also been investigated in detail, such as MRI (Balbus & Hawley 1991) or meridional circulation (Fung & Chiang 2016). Szulágyi et al. (2022) performed three-dimensional global hydrodynamic simulation that took into account radiative transport, gas viscosity, and back reactions from dust to gas, and investigated the dust supply to the CPD. Their results showed that vertical stirring of dust particles by spiral wakes excited by the planet’s gravity can play an important role in supplying solids to the CPD. Cilibrasi et al. (2023) performed three-dimensional global radiative magnetohydrodynamics (MHD) simulations. They found that a meridional circulation exists in the radiative MHD case, but high turbulent viscosity prevents gap opening, leading to a higher accretion rate than the hydrodynamic case. These simulations require a large amount of computer resource, but simulations with sufficiently high resolution will be important to examine, for example, distribution of captured solids in the CPD. It will also be important to clarify the degree of dust retention and its dependence on various parameters using global simulation with sufficiently high resolution. Li et al. (2023) performed three-dimensional global simulations of PPDs over gap-opening timescales and explore the planetary mass dependence of mass accretion rates onto the planet. They found that the scaling law is different from the local simulation of Maeda et al. (2022), probably due to the shearing box approximation not considering the global accretion of the PPD. This effect may also affect dust accretion.

Our calculations do not take into account the size distribution of dust particles. Recently, Karlin et al. (2023) performed multiple dust grain size simulations and showed that the dust behavior itself does not change with or without consideration of size distribution. This indicates that the superposition of the results of single-size simulations can be used to obtain the dust accretion rate onto the CPD in the presence of dust size distribution.

3.5 CONCLUSIONS

In this work, we performed orbital integration of solid particles approaching a planet, taking account of drag from the gas flow perturbed by the planet obtained by Maeda et al. (2022) using three-dimensional hydrodynamical simulations of a local region around a planet. We investigated the planetary-mass dependence of the orbits, capture positions, and capture rates of dust particles accreting onto the CPD. In addition, we examined the planetary-mass dependence of the degree of dust retention in accreting gas onto the CPD, which determines the ratio of dust-to-gas inflow rates, a key parameter in models of satellite formation in the CPD. The main results are as follows:

1. Similarly to the gas accretion band examined in our previous work (Chapter 2; see also Maeda et al. 2022), the initial orbits in the PPD of particles captured in the CPD distribute above the midplane continuously in the z -direction in a zonal pattern except near the midplane. For dust particles with $St \ll 1$, the radial width of the dust accretion band measured in units of the planet's Hill radius becomes wider with increasing planetary mass.
2. Dust particles accreting with the gas are supplied into a radially extended region of the surface of the CPD. Smaller particles tend to be captured in more inner regions of the CPD. Also, dust particles are captured in radially wider regions of the CPD in the case of a larger planetary mass.
3. The degree of dust retention in accreting gas onto the CPD increases with increasing planetary mass for a given dust scale height in the PPD. For the case of a small planet ($M_p = 0.2M_{\text{Jup}}$), particles with insufficient altitude in the PPD cannot get assisted by the accreting gas flow and cannot accrete onto the CPD. On the other hand, for the case of a massive planet ($M_p = 1M_{\text{Jup}}$), even in the case with a small dust scale height of $h_d = 0.1h_g$, the ratio of dust-to-gas inflow rates in the case of particles with $r_d = 10^{-4}$ to 10^{-2} m can be as large as 10 – 30% of the dust-to-gas mass ratio in the PPD (Figure 3.7).

The results of this study can be used to develop models of satellite formation around gas giants of various masses, e.g., Saturn, Jupiter, and exoplanets. Further investigation on the delivery of dust particles onto the CPD using improved numerical models, such as global simulation of dust and gas components taking into account of their back reactions will be desirable for better understanding of dust supply onto the CPD (§ 3.4.5). Also, the amount of dust supplied to the CPD is highly dependent on the dust scale height in the PPD, the structures of the gas and dust gaps, and the size distribution of dust particles in the PPD. Further observational studies on these quantities as well as their planetary mass dependence will be desirable to derive more information. In particular, given that giant planets are expected to cause meridional circulation (Tsukagoshi et al. 2019, Bi et al. 2021, Szulágyi et al. 2022), it is highly important to observe PPDs in the late stages of giant planet formation. Recently, CPD candidates around exoplanets have been detected, such as PDS70c and AS 209b (Isella et al. 2019, Bae et al. 2022), and a comparison of model calculations of dust evolution in the CPD with observations of dust thermal emissions is also being attempted (Shibaike & Mordasini, in preparation). These theoretical and observational studies will contribute to the development of more realistic satellite formation models.

Chapter 4

Size Distributions of Bluish and Reddish Small Main-belt Asteroids Obtained by Subaru/Hyper Suprime-Cam ^{*3}

4.1 INTRODUCTION

The main asteroid belt, located between the orbits of Mars and Jupiter, consists of asteroids with various spectral types. S-type and C-type are two of the most major types in the main-belt (DeMeo & Carry 2014). S-type asteroids are thought to have a rocky composition, and to be the parent bodies of ordinary chondrite meteorites because the abundance and spectral features are consistent with each other (e.g., Binzel et al. 2001, Burbine et al. 2002). However, the shapes of their spectra do not exactly match and this problem was previously recognized as a missing link between the asteroids and the meteorites. Understanding of space weathering was advanced by laboratory experiments (e.g., Sasaki et al. 2001) as well as spacecraft studies by NEAR Shoemaker (Prockter et al. 2002) and Hayabusa. The Hayabusa spacecraft brought a sample of an S-type asteroid (25143) Itokawa back to the Earth, and analysis of the sample revealed that S-type asteroids are parent bodies of ordinary chondrites (Nakamura et al. 2011). On the other hand, C-type asteroids are thought to have a carbon-rich composition with hydrous minerals (Usui et al. 2019, Potoszil et al. 2020). The Hayabusa2 spacecraft brought a sample of a C-type asteroid (162173) Ryugu back to the Earth. The sample analysis revealed that Ryugu samples are more primitive than CI chondrites, the closest samples to solar composition ever obtained by humankind (Yokoyama et al. 2023). More recently, the OSIRIS-REx, another sample-return mission for a C-group (a broader definition of C-type) asteroid (101955) Bennu, brought back samples that are currently being analyzed. These sample-return missions have made significant progress in understanding the exact composition of C-type asteroids.

S-type and C-type asteroids likely have different compositions, and their formation regions should also be different. In the current main-belt, S-type and C-type asteroids dominate in the inner-belt and the middle-/outer-belts, respectively, and their heliocentric distri-

^{*3}The content of this chapter is based on an author-created, un-copyedited version of an article published in The Astronomical Journal (Maeda et al. 2021). IOP Publishing Ltd is not responsible for any errors or omissions in this version of the manuscript or any version derived from it. The Version of Record is available online at <https://iopscience.iop.org/article/10.3847/1538-3881/ac2c6e>

butions partly overlap (DeMeo & Carry 2014, Yoshida & Nakamura 2007). This indicates that asteroids were mixed radially by some process (e.g., planetary migration) in the early Solar System (e.g., Walsh et al. 2011, Nesvorný 2018, Yoshida et al. 2019, 2020). Therefore, understanding the evolutions of asteroids with different spectral types can provide a clue to reveal the Solar System’s history. In the present work, we focus on the size distribution of asteroids with different spectral types. Since the current size distributions of asteroids are produced as a result of continuous collisional evolution, comparing the size distributions of asteroids with different spectral types is expected to provide important insights into their collisional evolution.

Many observational studies have been carried out about the size distribution of main-belt asteroids (MBAs; e.g., Jedicke & Metcalfe 1998, Ivezić et al. 2001, Yoshida et al. 2003, Yoshida & Nakamura 2004, 2007, Wiegert et al. 2007, Parker et al. 2008, Gladman et al. 2009, Terai et al. 2013, August & Wiegert 2013, Ryan et al. 2015, Peña et al. 2020). Some of them studied and compared the size distributions of MBAs with different spectral types. Ivezić et al. (2001) analyzed the Sloan Digital Sky Survey (SDSS) data and detected about 13,000 asteroids. They classified their asteroid sample into bluish and reddish groups, based on the principal component analysis using the $g - r$ and $r - i$ colors.^{*1} They obtained the size distribution for each group in the range of absolute magnitude $10 < H < 19$ ($1 \lesssim D \lesssim 40$ km, D : diameter). They approximated their cumulative size distribution with a power-law function

$$N(> D) \propto D^{-b}, \quad (4.1)$$

where $N(> D)$ is the number of asteroids with diameters larger than D . They found that the power-law indices of the size distributions of bluish/reddish groups agree with each other in the size range of $5 < D < 10$ km ($b = 4.00 \pm 0.05$) while they are slightly different in the size range of $3 < D < 5$ km ($b = 1.40 \pm 0.05$ for the bluish group and $b = 1.20 \pm 0.05$ for the reddish group). Yoshida & Nakamura (2007) performed a wide-field survey observation with the Suprime-Cam installed on the Subaru Telescope and detected about 1,000 MBAs. They classified their asteroid sample into bluish (C-like) and reddish (S-like) groups based on $B - R$ color, and obtained the size distributions for each group in the range of $14.6 < H < 20.2$. They found that the power-law indices of the bluish and reddish groups agree with each other within errors at $0.3 < D < 1$ km ($b = 1.33 \pm 0.03$ for bluish asteroids and $b = 1.29 \pm 0.02$ for reddish asteroids). These works showed slightly different results, and whether bluish and reddish asteroids have similar size distributions is still inconclusive.

In this study, we analyze data obtained by a wide-field survey observation with the Hyper Suprime-Cam installed on the 8.2 m Subaru Telescope. The observation detected over 3,000 small MBAs, and we measured the size distributions of bluish and reddish asteroids using a large homogeneous statistical sample about three times larger than Yoshida & Nakamura (2007), which allowed us to measure more accurate size distributions. This can provide a clue to better understanding of the collisional evolution of asteroids with different spectral types. The structure of this chapter is as follows. In § 4.2, we describe the survey observation and data analysis. In § 4.3, we show the results of color and size distributions. Comparison with previous works and implications of our results are presented in § 4.4. We summarize

^{*1}In the astronomical field, “color” means the difference in magnitude measured in different bands as defined by the photometric system, i.e., $g - r$ means the difference between the g - and r -band magnitudes. Customarily, objects with larger colors are described as “red” and those with smaller colors as “blue”.

our conclusions in § 4.5.

4.2 OBSERVATION AND DATA ANALYSIS

4.2.1 Observation

We used data obtained by the survey observation performed on January 26, 2015 (UT) using the Hyper Suprime-Cam (HSC) installed on the 8.2 m Subaru Telescope. HSC is a wide-field prime focus camera with 104 CCDs for science ($2048 \text{ pix} \times 4096 \text{ pix}$). The diameter of a field of view is 1.5 degrees with a pixel scale of 0.17 arcseconds (Miyazaki et al. 2018). The observation used the g -band (wavelength $0.40 - 0.55 \mu\text{m}$) and the r -band (wavelength $0.55 - 0.70 \mu\text{m}$) filters (Kawanomoto et al. 2018). We obtained the imaging data of eight fields near the opposition and the ecliptic plane, covering the sky area of about 14 deg^2 . The survey area is shown in Figure 4.1.

The observation procedure is as follows: First, we visited each field five times with the r -band at intervals of about 40 minutes. Next, we visited each field in the same way with the g -band. We can reduce the effect of brightness variation due to asteroids' rotation by averaging five values of an asteroid's flux obtained with each filter. The time of single exposure is 200 seconds. We summarize our observation in Table 4.1.

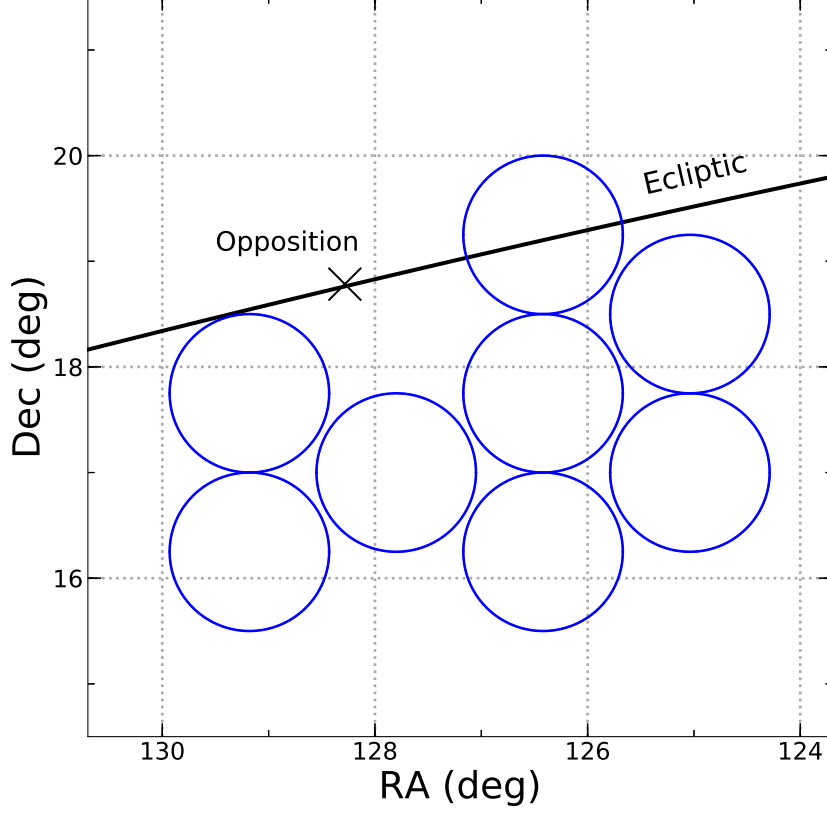


Figure 4.1: Locations of the surveyed fields of this work. Each circle represents the area covered by the field-of-view of HSC. The solid line shows the ecliptic plane. The cross shows the opposition on the observation day.

4.2.2 Image Reduction and Detection

We processed the data into calibrated images and created source catalogs using the hscPipe (ver.4.0.5), the HSC data reduction/analysis pipeline software (Bosch et al. 2018). We used the Pan-STARRS 1 (PS1) 3π catalog (Tonry et al. 2012, Schlafly et al. 2012, Magnier et al. 2013) for astrometric and photometric calibrations. The astrometric model in hscPipe includes a ninth-order polynomial distortion that is continuous over the full focal plane composed with distinct translation and rotation transforms for every CCD. For each visit, a different polynomial distortion is used for fitting (for details, see Bosch et al. 2018).

We used another software to extract candidates of moving objects from the lists of light sources detected by hscPipe based on the following conditions: (i) the sky motion is within the range of $\dot{\lambda} > -48 \text{ arcsec hr}^{-1}$ and $|\dot{\beta}| < -2.5\dot{\lambda} - 55 \text{ arcsec hr}^{-1}$, where $\dot{\lambda}$ and $\dot{\beta}$ are the motions along ecliptic longitude and latitude, respectively (see gray dot-dashed lines

Table 4.1: Observation log.

Field ID	UT	R.A. (h:m:s)	Decl. (d:m:s)	Filter	Seeing (arcsec)	Number of Detection
FIELD01	06:51 - 09:25	08:20:09	+18:30:00	<i>r</i>	0.59 - 0.99	468
	11:33 - 14:03			<i>g</i>	1.03 - 1.48	
FIELD02	06:55 - 09:29	08:25:41	+19:15:00	<i>r</i>	0.60 - 0.99	398
	11:38 - 14:07			<i>g</i>	0.98 - 1.69	
FIELD03	07:00 - 09:33	08:25:41	+17:45:00	<i>r</i>	0.54 - 0.90	405
	11:43 - 14:11			<i>g</i>	0.85 - 1.57	
FIELD04	07:05 - 09:37	08:36:43	+17:45:00	<i>r</i>	0.58 - 0.78	427
	11:48 - 14:15			<i>g</i>	1.02 - 1.55	
FIELD05	07:16 - 09:45	08:36:43	+16:15:00	<i>r</i>	0.55 - 0.69	439
	11:58 - 14:23			<i>g</i>	0.93 - 1.58	
FIELD06	07:21 - 09:49	08:31:12	+17:00:00	<i>r</i>	0.54 - 0.76	512
	12:03 - 14:27			<i>g</i>	1.11 - 1.78	
FIELD07	07:26 - 09:53	08:25:41	+16:15:00	<i>r</i>	0.59 - 0.95	363
	12:08 - 14:31			<i>g</i>	1.04 - 2.84	
FIELD08	07:31 - 09:56	08:20:09	+17:00:00	<i>r</i>	0.57 - 0.97	447
	12:13 - 14:35			<i>g</i>	1.15 - 1.65	

in Figure 4.2). (ii) the objects are detected from four or more out of five visits in the *r*-band data. Then, we searched each object in each *g*-band image based on the position and velocity measured in the *r*-band images assuming a constant motion on the sky. Finally, we checked all of the candidates with eyes to remove false detections. False detections are mainly blooming caused by electrons leaking from saturated pixels by a very bright object, or cosmic rays. The resulting data set contains 3,809 MBA candidates.

4.2.3 Measurements

We measured the fluxes of the detected MBAs by aperture photometry using the same technique as in Yoshida & Terai (2017). (i) We correct the centroid positions of each object by fitting an object model generated based on its motion and the seeing size of the image. (ii) We measure the flux of each object using a moving circular aperture formed based on the sky motion and the seeing size. If another source such as a field star exists in the aperture, we subtract another image taken at the same field from the original image using the Optimal Image Subtraction method (Alard & Lupton 1998, Bramich 2008) to measure the accurate flux of the target object. (iii) We convert the flux to magnitude using the photometric zero point measured by hscPipe. We defined the value of each object’s apparent magnitude for each band as the average of all the visits. We rejected objects for which we could not obtain apparent magnitudes in either *r*- or *g*-band, because we could not obtain $g - r$ color for such objects. Such unsuccessful measurements are mainly caused by the presence of bright stars in some of the apertures and the inability to properly subtract stars. Finally, we obtained both *r*- and *g*-band apparent magnitudes for 3,472 MBAs.

An apparent magnitude of an asteroid varies with time due to its rotation if it has a non-axisymmetric shape with respect to its spin axis. We estimated how our survey cadence reduced this effect using a Monte Carlo simulation. According to the previous studies for asteroids’ rotation period distribution, average values of the peak-to-peak amplitude and rotation period are 0.4 mag and 5.0 hours, respectively, for asteroids with a diameter of several kilometers (Waszczak et al. 2015, Pravec et al. 2002). Using these values, we generated 100,000 synthetic objects having a light curve given by a sinusoidal function with a random

initial rotation phase, and performed a virtual observation of these asteroids with conditions similar to our observations. We found that the standard deviations of their apparent magnitudes and colors are 0.034 mag and 0.066 mag, respectively, excluding the photometric uncertainties.

4.2.4 Orbit Estimation

We estimated the orbital elements for each of the detected asteroids from their apparent motion. Jedicke (1996) derived the relationship between an object's apparent motion velocity in ecliptic coordinates ($\dot{\lambda}$, $\dot{\beta}$) and its orbital elements, assuming that they are located near the opposition:

$$\begin{cases} \dot{\lambda} = \frac{\sqrt{GM_{\odot}}}{R-1} \left(\frac{\sqrt{a(1-e^2)}}{R} \cos I - 1 \right), \\ \dot{\beta} = \pm \frac{\sqrt{GM_{\odot}}}{R(R-1)} \sqrt{a(1-e^2)} \sin I, \end{cases} \quad (4.2)$$

where a , I , e , and R are the object's semi-major axis, inclination, eccentricity, and heliocentric distance, respectively. G and $M_{\odot}$ are the gravitational constant and the mass of the Sun, respectively. We cannot determine the orbital elements of detected asteroids accurately, because we performed our survey observation only one night. Therefore, we estimated their semi-major axis a and inclination I under the assumptions that they are on circular orbits and were observed at the opposition (i.e., $e = 0$, $R = a$, $\lambda' = 0^\circ$, $\beta = 0^\circ$, where λ' is ecliptic longitude from the opposition). These parameters were determined as the best-fit values for the Equations (4.2) with the measured sky motion through a least-square method. If the square root of the sum of squared residuals is larger than $0.01 \text{ arcsec hr}^{-1}$, we remove the object from our sample (we removed 13 asteroids for this reason). We show the distribution of apparent velocities of 3,472 asteroids in Figure 4.2. The removed asteroids are shown with blue crosses. We obtained a sample of 3,459 MBAs for which g - and r -band magnitudes as well as orbital elements are successfully obtained. We show the distribution of their orbital elements in Figure 4.3 (we will explain the classification into C-like/S-like asteroids in § 4.3.3).

The statistical errors in the obtained orbital elements were estimated by a Monte Carlo simulation as follows (Terai et al. 2013, Nakamura & Yoshida 2002): (i) We generate 100,000 synthetic asteroids randomly distributed in our survey field. The orbital elements of these asteroids are given with pseudo-random numbers that follow the distribution of orbital elements of known MBAs taken from the ASTORB database (Bowell et al. 1994). (ii) We calculate their apparent motion velocities under the same condition as our survey, and estimate their orbital elements from their apparent motion using Equations (4.2) under the assumptions of circular orbits and observation near the opposition. We found that the root mean square errors of estimated a , I , R , and the object's geocentric distance Δ are $\sigma_a = 0.12 \text{ au}$, $\sigma_I = 6.8^\circ$, $\sigma_R = 0.35 \text{ au}$, and $\sigma_{\Delta} = 0.35 \text{ au}$, respectively. These values are roughly consistent with the previous works that used the same method (Terai et al. 2013, Nakamura & Yoshida 2002).

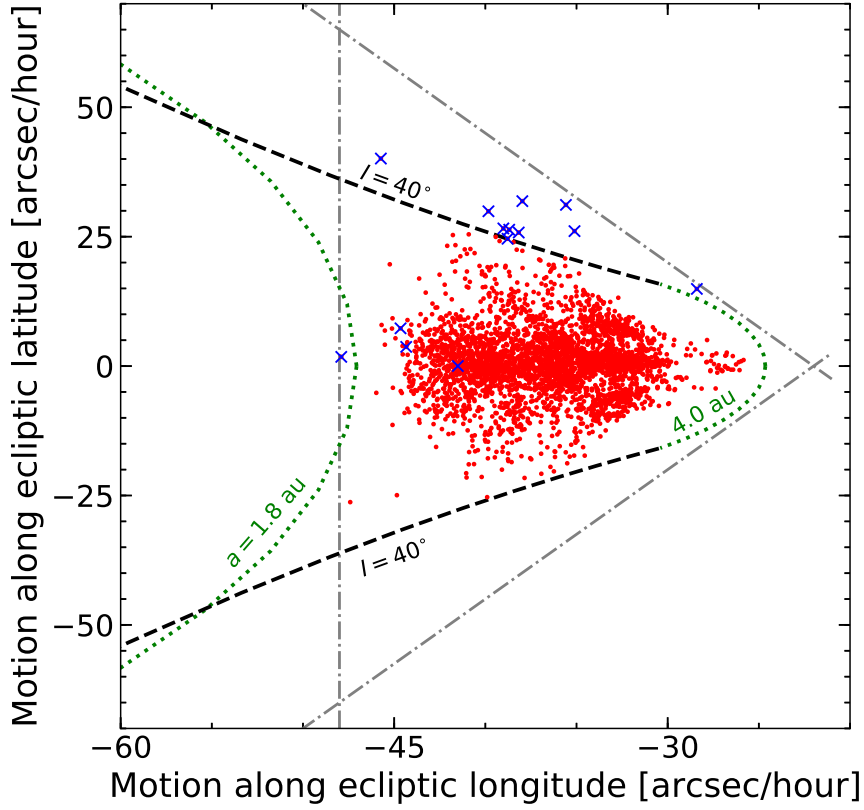


Figure 4.2: Distribution of apparent velocities of the detected moving objects. The horizontal axis shows the motion along the ecliptic longitude $\dot{\lambda}$, and the vertical axis shows the motion along the ecliptic latitude $\dot{\beta}$. The objects for which photometric measurements with both r - and g -bands were successfully performed are plotted. The blue crosses show the objects eliminated from the sample because of large residuals (see text). The gray dot-dashed lines show the conditions for our MBA detection (§ 4.2.2), i.e., $\dot{\lambda} > -48 \text{ arcsec hr}^{-1}$ and $|\dot{\beta}| < -2.5\dot{\lambda} - 55 \text{ arcsec hr}^{-1}$. The green dotted lines show $a = 1.8 \text{ au}$ (left) and $a = 4.0 \text{ au}$ (right), respectively, assuming $R = a$ and $e = 0$ in Equations (4.2). The black dashed lines show $I = 40^\circ$, $R = a$, and $e = 0$ in Equations (4.2).

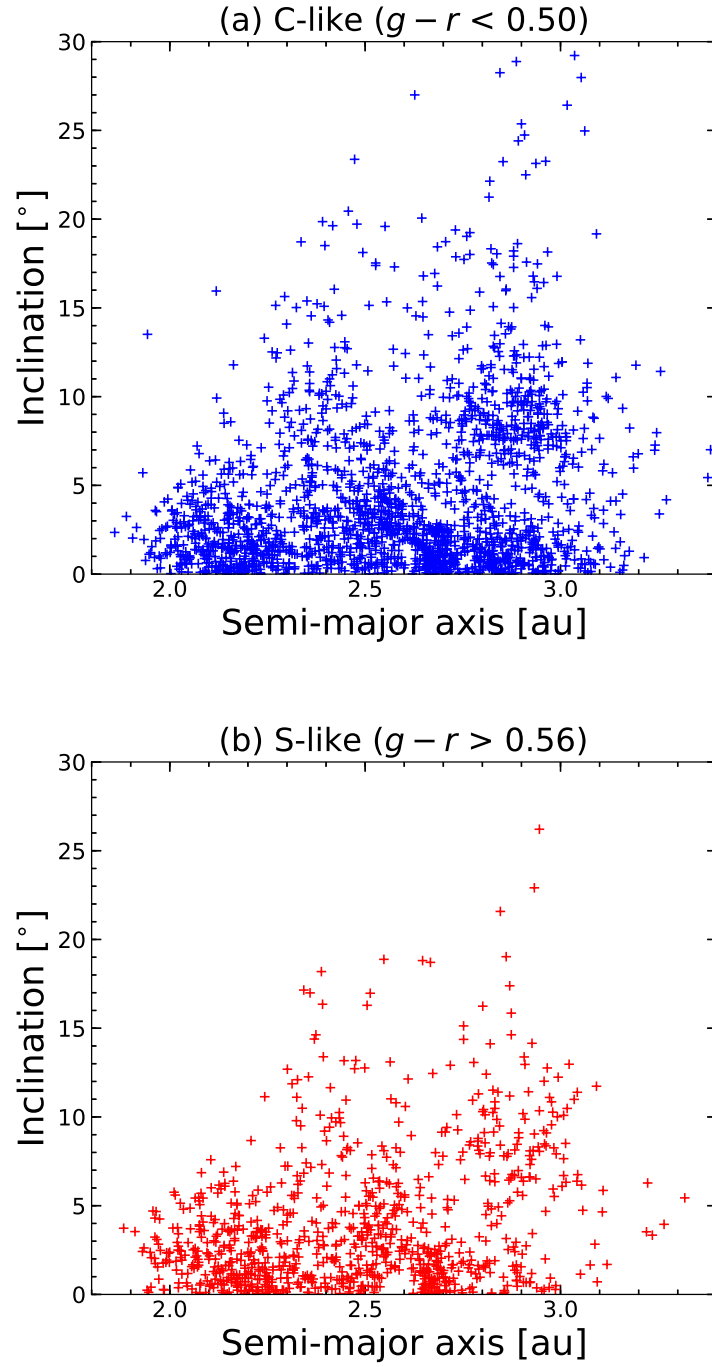


Figure 4.3: Semi-major axis vs. inclination of each object in our sample. (a) C-like asteroids ($g - r < 0.50$) and (b) S-like asteroids ($g - r > 0.56$). See § 4.3.3 for the classification of these two groups.

4.3 RESULTS

4.3.1 Sample Selection

We derived the absolute magnitude of each asteroid from its apparent magnitude m , heliocentric distance R , and geocentric distance Δ as (Bowell et al. 1989)

$$H = m - 5 \log(R\Delta) - P(\theta), \quad (4.3)$$

where $P(\theta)$ is the phase function at a solar phase angle θ described as

$$P(\theta) = -2.5 \log[(1 - G)\Phi_1 + G\Phi_2]. \quad (4.4)$$

In the above, G is the slope parameter. We use a typical value of MBAs, $G = 0.15$ (Bowell et al. 1989), because there is no way to obtain magnitudes at various solar phase angles in this survey. Φ_1 and Φ_2 are functions of θ given as

$$\begin{aligned} \Phi_i &= \exp(-A_i[\tan(\theta/2)]^{B_i}) \quad (i = 1, 2), \\ A_1 &= 3.33, \quad A_2 = 1.87, \quad B_1 = 0.63, \quad B_2 = 1.22. \end{aligned} \quad (4.5)$$

We can describe an error of absolute magnitude σ_H considering error propagation as follows:

$$\sigma_H = \sqrt{\sigma_m^2 + \left(-\frac{5}{\ln 10} \frac{\sigma_R}{R}\right)^2 + \left(-\frac{5}{\ln 10} \frac{\sigma_\Delta}{\Delta}\right)^2}, \quad (4.6)$$

where σ_m is the photometric error of apparent magnitude. As we described in § 4.2.4, the errors of heliocentric and geocentric distances are $\sigma_R = \sigma_\Delta = 0.35$ au. Therefore, we can estimate the error of absolute magnitude to be $\sigma_H \simeq 0.4 - 0.8$ mag.

To eliminate biases induced by detection incompleteness, we set the detection limit magnitude of our survey based on detection efficiencies. We examined the detection efficiency through the data reduction procedure with implanted synthetic moving objects (see Yoshida & Terai 2017 for details). Then, the detection efficiency for each CCD image obtained as a function of the apparent magnitude m of implanted objects is fit by the following function

$$\eta(m) = \eta_0 \sum_{k=1,2} \frac{\epsilon_k}{2} \left[1 - \tanh\left(\frac{m - m_{50}}{w_k}\right) \right] \quad (4.7)$$

with

$$\epsilon_1(m) = 1 - \epsilon_2(m) = \frac{1}{2} \left[1 - \tanh\left(\frac{m - m_{50}}{0.2}\right) \right], \quad (4.8)$$

where η_0 is the maximum value of the detection efficiency, m_{50} is the apparent magnitude where detection efficiency is $\eta_0/2$, and w_k ($k = 1, 2$) is the transition width. We calculate the best-fit parameter values of detection efficiencies for all the exposures for each CCD and set 24.2 mag as the detection limit of apparent magnitude where the detection efficiency is 50% or more for most ($\sim 90\%$) of the exposure/CCD images. Figure 4.4 shows the plots of R and H_r for each of the 3,459 objects in our sample (we will explain the classification into C-like/S-like asteroids in § 4.3.3). We defined the outer edge of our MBA sample as $R = 3.0$ au, where $m_r = 24.2$ mag corresponds to $H_r = 20.3$ mag. Thus, we select objects

with $R \leq 3.0$ au and $H_r \leq 20.3$ mag as an unbiased sample. We also investigated absolute magnitude distribution for each region divided by a heliocentric distance 2.6 au, i.e., inner region ($R \leq 2.6$ au) and outer region ($2.6 \leq R \leq 3.0$ au), respectively. The detection limit for the inner region corresponds to $H_r = 21.1$ mag. Note that the above choice of the boundaries of the inner and outer regions does not greatly affect our main results (§ 4.3.5).

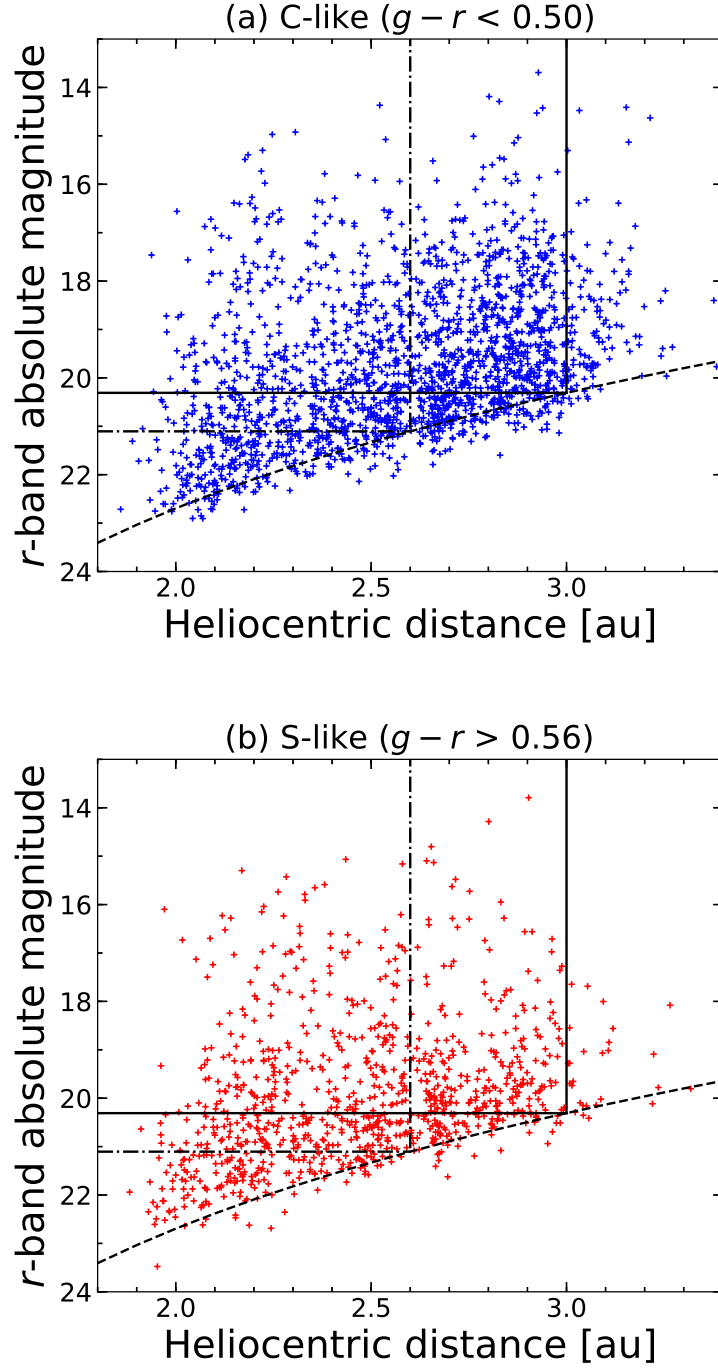


Figure 4.4: Heliocentric distance vs. r -band absolute magnitude of each object in our sample. (a) C-like asteroids ($g - r < 0.50$) and (b) S-like asteroids ($g - r > 0.56$). See § 4.3.3 for the classification of these two groups. The dashed line shows apparent magnitude of $m_r = 24.2$ mag. The solid lines show the detection limit of the whole region, i.e., heliocentric distance of $R = 3.0$ au and absolute magnitude of $H_r = 20.3$ mag. The dot-dashed lines show the detection limit for the inner region, i.e., heliocentric distance of $R = 2.6$ au and absolute magnitude of $H_r = 21.1$ mag.

4.3.2 Color Distributions

Figure 4.5 shows the histogram of the $g - r$ color of our unbiased sample (§ 4.3.1). In addition to the case of the whole sample, we also plotted the cases limited by various apparent magnitudes m_r . When the sample is limited to those with $m_r < 21.5$ mag (blue dotted line) or $m_r < 20.5$ mag (green dot-dashed line), a structure that may be regarded as double peaks is seen in the color distribution. The peaks are located at $g - r \sim 0.4$ and 0.6^{*2} , respectively, which roughly correspond to those of the C-type and S-type asteroids, respectively, seen in the 4th release of SDSS Moving Object Catalog (SDSS MOC4, Ivezić et al. 2010, Hasselmann et al. 2011; see § 4.3.3, Figure 4.6). Although the double peaks are expected to be hidden considering the color uncertainties induced by photometry and asteroids' rotation, two populations can be recognized when the photometric error is low enough ($m_r \lesssim 21.5$ mag).^{*3}

Some previous works reported a bimodal color distribution of MBAs, while others found no such dichotomy. Ivezić et al. (2001) found bimodal distributions in the color-color diagrams plotted for objects whose photometric errors are less than 0.05 mag, while they showed that the color dichotomy becomes unclear for fainter objects as we found in Figure 4.5. Yoshida & Nakamura (2007) reported bimodality of $B - R$ color distribution of sub-km to km-sized MBAs, although it was unclear for the sample for the middle and outer main-belt. Gladman et al. (2009) found no color dichotomy even though their sample has a small error of absolute magnitudes (the error values are 0.11 au and 0.36 mag in heliocentric distance and absolute magnitude, respectively) due to accurate orbits obtained by multiple-night observations. Peña et al. (2020) measured $g' - r'$ colors of about 1,000 MBAs with orbits determined and found no significant color dichotomy, which might be caused by uncertainty in absolute magnitudes due to asteroid rotation.

^{*2}Customarily, the notation $g - r$ is used instead of $m_g - m_r$. The colors in other wavelength bands are represented similarly, such as $B - R$.

^{*3}We tested the visibility of the bimodality of color distribution and found that the double peak cannot be seen when a color uncertainty is assumed to be 0.066 mag as large as the rotational effect of our sample. Also, other effects such as space weathering are likely to have relatively minor contributions to the shape of the color distribution^{*4}.

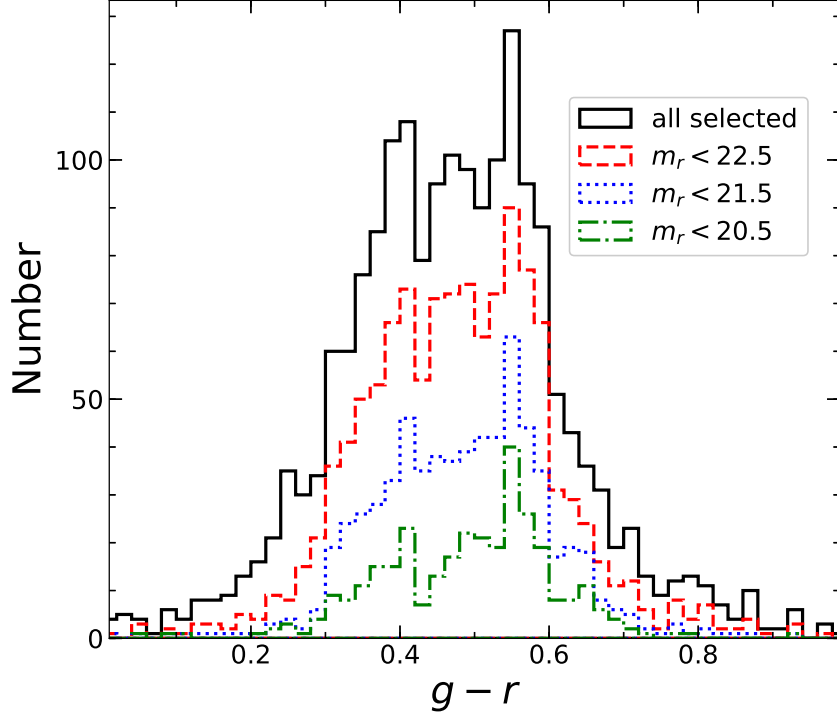


Figure 4.5: Histogram of the $g - r$ colors of our unbiased sample. Different lines represent the cases limited by different apparent magnitudes: black for all the selected sample, red for $m_r < 22.5$ mag, blue for $m_r < 21.5$ mag, and green for $m_r < 20.5$ mag.

4.3.3 Color Classification

Using the $g - r$ color of each asteroid, we classified our sample into two groups, i.e., bluish C-like asteroids and reddish S-like asteroids. In order to define the classification criterion, we use the SDSS MOC4. We corrected the color of each asteroid in the SDSS MOC4 to that in HSC’s filter system, and classified these objects into spectral types according to the taxonomy given by Carvano et al. (2010) and Hasselmann et al. (2011) (C_p , S_p , etc.). Figure 4.6 shows the $g - r$ color histogram of C_p -/ S_p -type asteroids in the SDSS MOC4. The curves show the fraction of asteroids belonging to each of the two types for each color bin; for example, the blue curve shows (the number of C_p -type asteroids)/(the total number of C_p -type and S_p -type asteroids) for each bin. We defined the classification criteria by the $g - r$ color values where the fraction is 0.9; those with $g - r < 0.50$ are defined as C-like asteroids and those with $g - r > 0.56$ as S-like asteroids. In this way, we can get less-contaminated samples than the previous works, Ivezić et al. (2001) and Yoshida & Nakamura (2007), which used a single color boundary between bluish and reddish groups.

We evaluated the accuracy of our classification using the SDSS MOC4 asteroids. We classified C_p -type and S_p -type of the SDSS MOC4 asteroids into C-like and S-like by our classification criteria, respectively. Table 4.2 is the confusion matrix of the color classification using the SDSS MOC4 asteroids. We found that the recall of C_p -type (the fraction of asteroids classified as C-like among all actual C_p -type asteroids) is 99.1%, and the recall of

S_p -type (the fraction of asteroids classified as S-like among all actual S_p -type asteroids) is 99.3%. We also found that the precision of C-like (the fraction of actual C_p -type asteroids among all asteroids classified as C-like) is 99.4%, and the precision of S-like (the fraction of actual S_p -type asteroids among all asteroids classified as S-like) is 98.9%. The F_1 -scores of C-like and S-like are 99.3% and 99.1%, respectively.

Table 4.2: Confusion matrix of the color classification using the SDSS MOC4 asteroids.

		Classified		
		C-like	S-like	Recall
Actual	C_p -type	25472	236	99.1%
	S_p -type	148	21602	99.3%
	Precision	99.4%	98.9%	

Note. The rows show the actual types (C_p -type or S_p -type) of classified asteroids, and the columns show their classified types (C-like or S-like).

It should be noted that each of the above two groups likely contains asteroids with other spectral types because we use only the $g - r$ color. C-like asteroids likely contain D and X-types as well as their complexes. Also, S-like asteroids likely contain L, Q, V, D, X, A-types and their complexes.

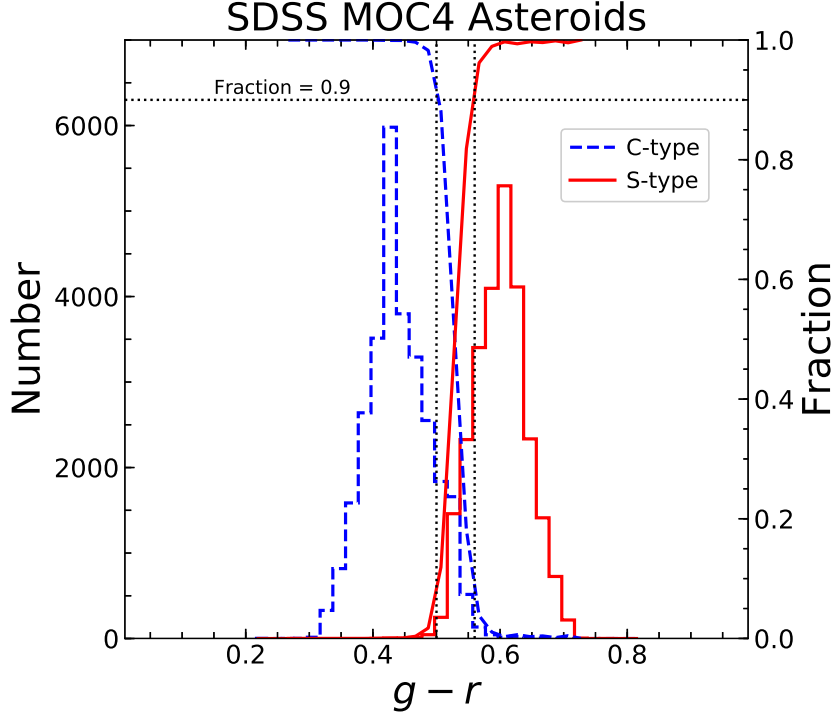


Figure 4.6: Histogram of the $g - r$ colors for the SDSS MOC4 (Ivezić et al. 2010, Hasselmann et al. 2011) C_p-type (blue dashed-lines) and S_p-type (red solid-lines) asteroids corrected for the difference of the filter systems between HSC and SDSS. The classification for each spectral type is based on the Carvano et al. (2010) taxonomy. The curves show the fraction of asteroids belonging to each type in each color bin. The horizontal dotted line shows the fraction of 0.9, and the vertical dotted lines show the color boundaries used for our classification into C-/S-like asteroids, corresponding to the $g - r$ colors at the fraction of 0.9 for each type.

4.3.4 Comparison of Size Distributions of C-like and S-like Asteroids

Based on the photometric measurements and color classification described above, we obtained absolute magnitude distributions for our MBA sample. Figures 4.7(a), (b), and (c) show the absolute magnitude distributions for all, C-like, and S-like asteroids, respectively. The cumulative numbers shown on the vertical axis are corrected by the detection efficiency for each asteroid (Yoshida & Terai 2017):

$$N(< H) = \sum_{j: H_j < H} \frac{1}{\eta(m_j)}, \quad (4.9)$$

where $\eta(m_j)$ is the detection efficiency of the j -th object with apparent magnitude m_j in the r -band. As described in § 4.2.2, the sample objects were detected from four or five r -band images. In this case, the detection efficiency of an asteroid in all the four images taken for a certain field is given by (Yoshida & Terai 2017):

$$\eta(m) = \prod_{i=1}^4 \eta_i(m). \quad (4.10)$$

where $\eta_i(m)$ is the detection efficiency of this object in the i -th image. We estimated $\eta(m)$ as a product of the largest four values of η_i for each object.

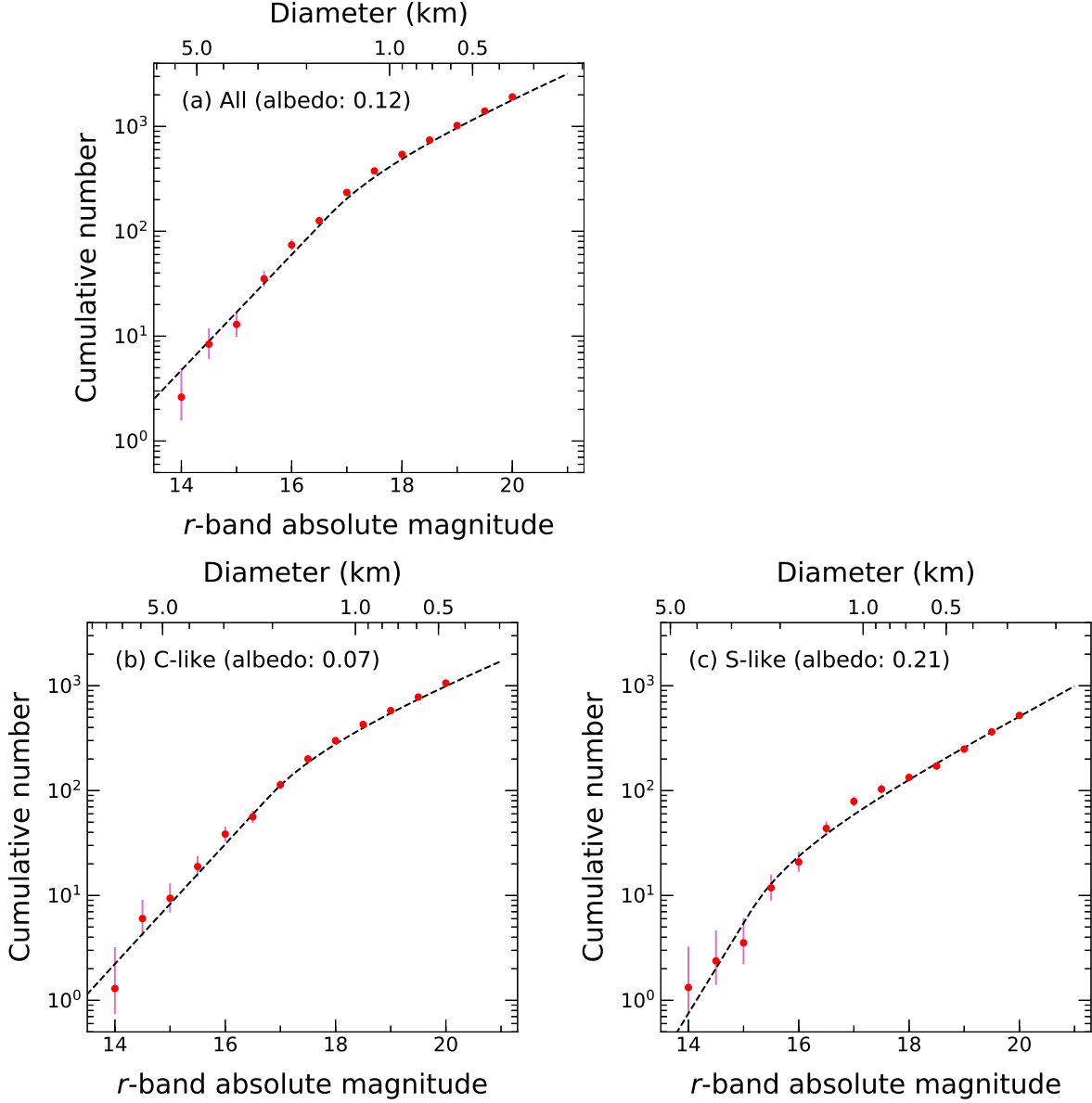


Figure 4.7: Distributions of the r -band absolute magnitudes of the objects in our unbiased sample for the whole region. (a) all asteroids, (b) C-like asteroids ($g - r < 0.50$), and (c) S-like asteroids ($g - r > 0.56$), respectively. The red dots show cumulative number of the asteroids for each bin. The bin width is 0.5 mag. The error bars represent Poisson's statistical error. The dashed lines show the best-fit models (see Table 4.3). Diameters shown on the upper horizontal axis were obtained by converting from absolute magnitudes under the assumption of a constant albedo of (a) $p = 0.12$, (b) $p = 0.07$, and (c) $p = 0.21$, respectively (see § 4.3.4).

In order to compare the size distributions of C-like and S-like asteroids, we convert the absolute magnitude of an asteroid to its diameter using the following equation:

$$\log D = 0.2r_{\odot} - \log \frac{\sqrt{p}}{2R_{\oplus}} - 0.2H_r, \quad (4.11)$$

where $r_{\odot} = -26.91$ is the r -band magnitude of the Sun (Fukugita et al. 2011), p is a

geometric albedo, and $R_{\oplus}$ is the heliocentric distance of the Earth (i.e., 1 au). We assumed the constant albedo of $p = 0.07$, $p = 0.21$, and $p = 0.12$ for C-, S-like, and all asteroids, respectively, based on the mean values of the C-, S-type, all MBAs measured by the infrared astronomical satellite AKARI (Usui et al. 2013).

Figure 4.8 shows a direct comparison of the cumulative size distributions between the C- and S-like asteroids. The cumulative number in the vertical axis is normalized by the value at $D = 0.4$ km, which corresponds to the detection limit of the C-like asteroids. The error bars show Poisson's statistical error. We found that the shapes of the cumulative size distributions of C- and S-like samples agree with each other within statistical errors for $0.4 < D < 1.5$ km.

We evaluated the goodness of the agreement by the Kolmogorov-Smirnov test (hereafter KS test, Press et al. 1992). The statistic D_{KS} of the KS test is defined by the maximum deviation between two cumulative distribution functions $S_1(x)$ and $S_2(x)$ as

$$D_{\text{KS}} = \max |S_1(x) - S_2(x)|. \quad (4.12)$$

The significance probability is approximately calculated by the following function:

$$P(D_{\text{KS}} > \lambda) = Q_{\text{KS}}(\sqrt{n_1 n_2 / (n_1 + n_2)} D_{\text{KS}}) \quad (4.13)$$

with

$$Q_{\text{KS}}(\lambda) = 2 \sum_{j=1}^{\infty} (-1)^{j-1} e^{-2j^2 \lambda^2}, \quad (4.14)$$

where n_1 and n_2 are numbers of data points of $S_1(x)$ and $S_2(x)$, respectively.

We performed the KS test under the null hypothesis that the two samples are drawn from the same distribution in the size range of $0.4 < D < 4.7$ km. We found that the significance probability is 0.218, i.e., the null hypothesis cannot be rejected at a 20% significance level.^{*5} We confirmed that even when we set the classification criterion of C- and S-like samples more strictly (for example, $g - r < 0.40$ for the C-like asteroids, and $g - r > 0.60$ for the S-like asteroids), the significance probability is no less than 0.2.

^{*5}When the significance probability is less than the assumed significance level, the null hypothesis can be rejected, i.e., both samples are likely drawn from populations that follow different distributions.

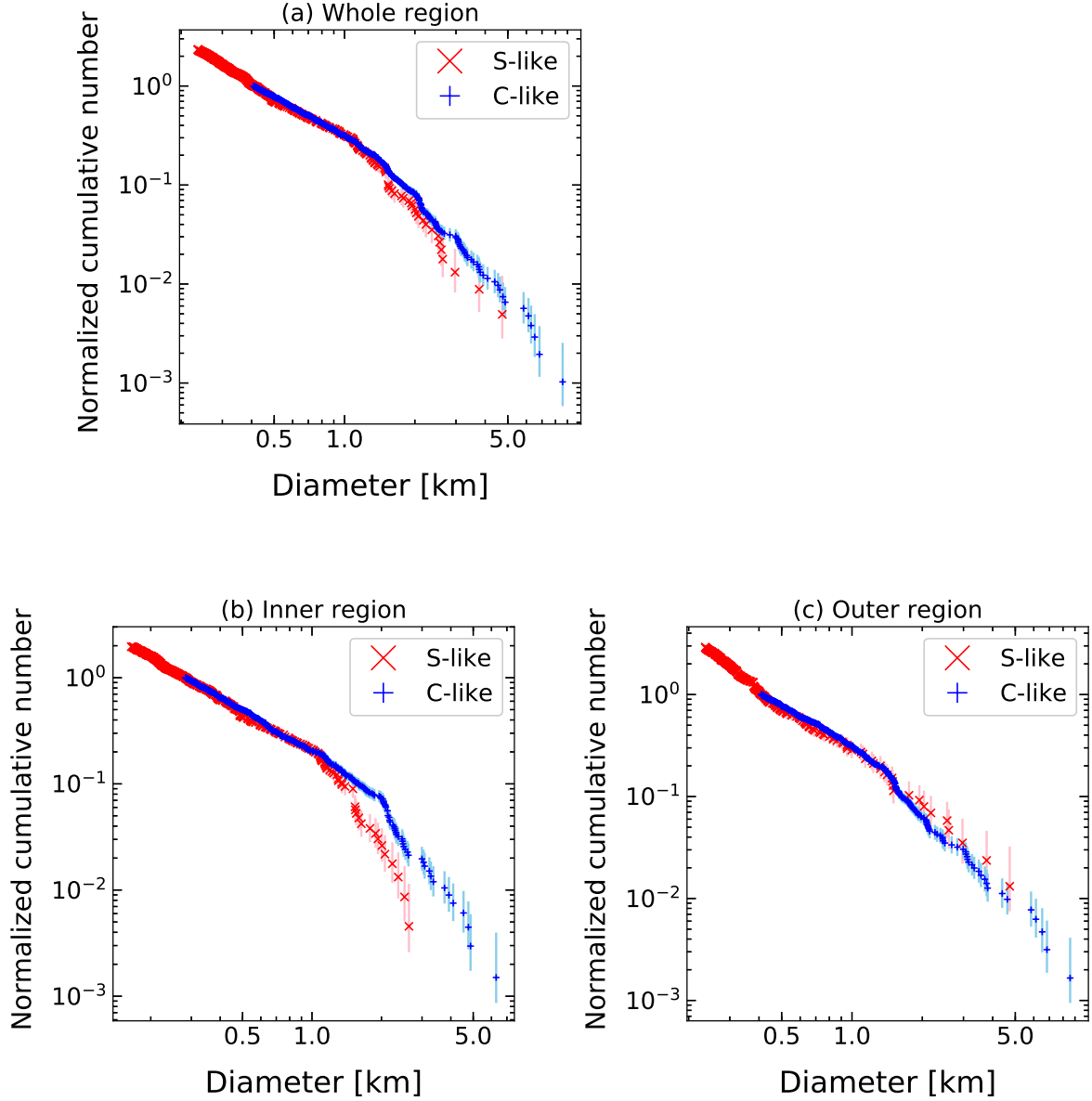


Figure 4.8: Cumulative size distributions of bluish C-like asteroids ($g - r < 0.50$; shown by blue pluses) and reddish S-like asteroids ($g - r > 0.56$; shown by red crosses). (a), (b), and (c) are for the whole region, the inner region ($1.8 < a < 2.6$ au), and the outer region ($2.6 < a < 3.0$ au), respectively. The values of the vertical axis are normalized by the values at $D = 0.4$ km. Diameters are obtained by converting from absolute magnitudes under the assumption of a constant albedo of $p = 0.07$ for C-like asteroids, and $p = 0.21$ for S-like asteroids (Usui et al. 2013), respectively.

To measure the slopes of obtained absolute magnitude distributions, we approximated the differential absolute magnitude distributions $\Sigma(H) = dN(H)/dH$ with the following

broken power-law:

$$\Sigma(H) = \begin{cases} 10^{\alpha_1(H-H_0)} & (H < H_{\text{break}}), \\ 10^{\alpha_2 H + (\alpha_1 - \alpha_2)H_{\text{break}} - \alpha_1 H_0} & (H \geq H_{\text{break}}), \end{cases} \quad (4.15)$$

where α_1 and α_2 are the power-law indices of the absolute magnitude distributions for the brighter and fainter ends, respectively. H_{break} is the absolute magnitude of the breakpoint, and H_0 is defined so that $\Sigma(H_0) = 1$. We used the maximum-likelihood method (Bernstein et al. 2004, Yoshida & Terai 2017) to obtain the best-fit parameters of Equations (4.15). For the numerical analysis of the maximum-likelihood estimation, we used the Markov Chain Monte Carlo method (MCMC) with a Python package `emcee`^{*6} (Foreman-Mackey et al. 2013). Figure 4.9 shows the post-event distributions of sampling for each parameter by MCMC for the whole region. We adopted a maximum a posteriori (MAP) as the best-fit value for each parameter.

The best-fit parameters are shown in Table 4.3. In all the cases of the all, C-like, and S-like asteroids, the slope α changes at $H \sim 15 - 17$ mag and the slopes at the fainter end are shallower than those at the brighter end. The slopes in the fainter end are $\alpha_2 = 0.21^{+0.01}_{-0.01}$ and $\alpha_2 = 0.28^{+0.01}_{-0.01}$ for C-/S-like asteroids, respectively. On the other hand, the slopes in the brighter end are $\alpha_1 = 0.57^{+0.01}_{-0.07}$ and $\alpha_1 = 0.86^{+0.11}_{-0.15}$ for C-/S-like asteroids, respectively. Note that the slopes in the brighter end have large uncertainties due to the small sample number, which was partly caused by CCD saturation for bright objects.

^{*6}<https://emcee.readthedocs.io/en/stable/>

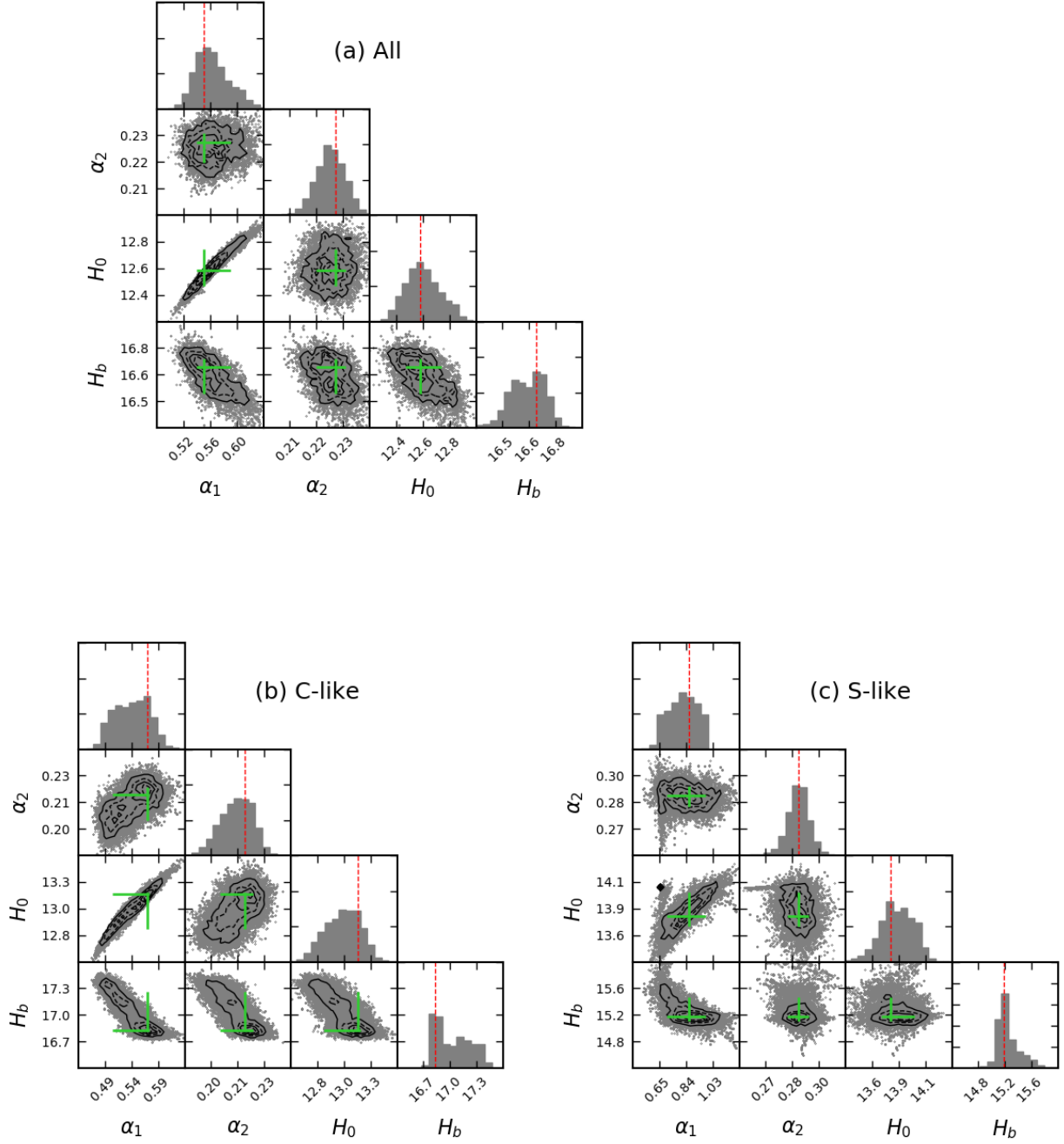


Figure 4.9: Post-event distributions of sampling by MCMC for the whole region. The red dashed lines in the 1D histograms show the best-fit values. Each gray point in the 2D histograms (black contours) shows the result of sampling for each step. The green crosses in the 2D histograms show the error range of the best-fit.

In Figure 4.7 (c) for S-like asteroids, we notice a significant deviation of the model from the data at $H \sim 17$ mag, while they agree well with each other for the cases of all and C-like asteroids. We confirmed that the absolute magnitude distribution for S-like asteroids cannot

Table 4.3: Numbers of asteroids in our sample and best-fit parameters for the absolute magnitude distributions.

Types	number	α_1	α_2	H_0	H_{break}
All	1814	$0.55^{+0.04}_{-0.01}$	$0.23^{+0.01}_{-0.01}$	$12.58^{+0.17}_{-0.12}$	$16.69^{+0.04}_{-0.13}$
C-like	1026	$0.57^{+0.01}_{-0.07}$	$0.21^{+0.01}_{-0.01}$	$13.18^{+0.02}_{-0.33}$	$16.80^{+0.46}_{-0.01}$
S-like	479	$0.86^{+0.11}_{-0.15}$	$0.28^{+0.01}_{-0.01}$	$13.80^{+0.20}_{-0.09}$	$15.14^{+0.29}_{-0.06}$

be approximated well with Equations (4.15) due to the partial excess at $H \sim 17$ mag, even after fine-tuning of the parameters.

In Figure 4.8 (a), the fainter-end slopes of C-like and S-like asteroids agree with each other, but the best-fit values of α_2 are slightly different between them. One reason for this is the discrepancy between the model and the data described above. Another reason is underestimating the number of brighter S-like asteroids mainly because of saturation, which makes the best-fit distribution of S-like asteroids steeper than the actual distribution. To accurately evaluate the fainter-end slope, we fit a broken power-law to the S-like asteroid sample again assuming the same values of α_1 (0.54) and the diameter at the break corresponding to $H_{\text{break}} = 15.79$ as the best-fit parameters for the C-like asteroid sample. We found that the best-fit value is $\alpha_2 = 0.234 \pm 0.002$, which is quite similar to that of the C-like asteroids.

4.3.5 Heliocentric Distance Dependence

We also compared the size distributions for the C- and S-like asteroids in each of the inner and outer regions, separately (Figures 4.8 (b) and (c)). For the inner region ($1.8 < a < 2.6$ au), we found that the shapes of the size distributions of C- and S-like asteroids agree with each other within the statistical errors at $0.3 < D < 1.0$ km. The discrepancy in $D > 1.0$ km may be caused by undetected bright S-like asteroids due to saturation. The saturation magnitude of our survey is around $m_r = 17.5$ mag, which corresponds to $H_r \simeq 14.5 - 16$ mag ($D = 1.7 - 3.4$ km for S-like asteroids) in the inner region. Therefore, underestimation due to saturation is likely to appear for $D \gtrsim 1.7$ km for S-like asteroids ($p = 0.21$) in the inner region^{*7}. For the outer region ($2.6 < a < 3.0$ au), we found that the shapes of the size distributions of C- and S-like asteroids agree with each other within the errors at $0.4 < D < 4.5$ km. We performed the KS test under the null hypothesis that the two samples are drawn from the same distribution in the size ranges of $0.3 < D < 2.6$ km and $0.4 < D < 4.7$ km for the inner and outer region, respectively. We found that the significance probabilities are 0.94 for the inner region and 0.36 for the outer region, respectively, i.e., the null hypothesis cannot be rejected at a 20% significance level for both regions. For the inner region, we also performed the Anderson-Darling test (Anderson & Darling 1952), which is corrected for effects of edges of distributions, and found that the significance probability is 0.107, and the null hypothesis cannot be rejected at a 10% significance level. We also found that their shapes agree with each other within the errors, at least in the size range of $0.4 < D < 1.0$ km, even when we change the heliocentric boundary between the two

^{*7}For C-like asteroids ($p \sim 0.07$), the saturation effect is likely to appear for $D \gtrsim 3.4$ km in the inner region.

regions by about 0.1 au. It should be noted that the uncertainty of semi-major axis for our sample is $\sigma_a = 0.12$ au (§ 4.2.4), thus we have to keep this in mind when discussing the difference between different radial locations.

4.4 DISCUSSION

4.4.1 Comparison with Previous Works

Yoshida & Nakamura (2007) measured size distributions of C-like ($B - R < 1.1$) and S-like ($B - R > 1.1$) asteroids obtained by a survey observation with the Suprime-Cam on the Subaru Telescope. They found that the slopes for C- and S-like asteroids agree with each other within errors in the fainter end but disagree in the brighter end. The cumulative size distribution of their C-like sample was approximated by a single power-law with the slope of $b = 1.33 \pm 0.03$ for $0.6 < D < 6.5$ km ($\alpha = 0.27 \pm 0.01$ for $14.6 < H < 20.2$ mag), and that of their S-like sample was approximated by a broken power-law with the slopes of $b_1 = 2.44 \pm 0.09$ for $1.0 < D < 2.3$ km ($\alpha_1 = 0.49 \pm 0.02$ for $15.4 < H < 17.0$ mag) and $b_2 = 1.29 \pm 0.02$ for $0.3 < D < 1.0$ km ($\alpha_2 = 0.26$ for $17.4 < H < 20.2$ mag), respectively, where b_1 and b_2 are brighter/fainter end slopes of a cumulative size distribution represented by a broken power-law (they have the relationship $b_1 = 5\alpha_1$ and $b_2 = 5\alpha_2$, respectively, with the corresponding absolute magnitude distribution slopes α_1 and α_2). Ivezić et al. (2001) measured the size distributions of blue (C-like) and red (S-like) asteroids, which are obtained by SDSS and classified based on the principal component analysis using $g - r$ and $r - i$ colors. They found that the slopes of cumulative size distributions for the brighter ends are $b_1 = 4.00 \pm 0.05$ ($\alpha_1 = 0.80 \pm 0.01$) for both the blue and the red (the size range was $5 \lesssim D \lesssim 20$ km for the blue, and $5 \lesssim D \lesssim 40$ km for the red), and that for the fainter ends are $b_2 = 1.40 \pm 0.05$ ($\alpha_2 = 0.28 \pm 0.01$) for the blue for $3 \lesssim D \lesssim 5$ km, and $b_2 = 1.20 \pm 0.05$ ($\alpha_2 = 0.24 \pm 0.01$) for the red for $0.7 \lesssim D \lesssim 5$ km (see Yoshida et al. 2019 for a discussion of the limiting diameters of their size distributions). Peña et al. (2020) measured g' - and r' -band absolute magnitude distributions for $14 < H_{g'} < 18$ mag ($1 < D < 10$ km) with 1,182 MBAs detected from HiTS 2015 data. They did not find any color dependence in the derived absolute magnitude distributions.

These studies showed that both of the C-like and S-like asteroids have similar size distributions with a power-law index of $b \simeq 1.2 - 1.4$ ($\alpha \simeq 0.24 - 0.28$) for diameters smaller than several kilometers, but their results have a slight discrepancy. We confirmed that the size distribution of C- and S-like asteroids have similar shapes at sub-km, and both of them have a break point at $D \sim 2$ km. From the results of Ivezić et al. (2001), Peña et al. (2020), and the present work, the similarity of the shapes of the size distributions between C-like and S-like asteroids seems to hold up to ~ 10 km in diameter.

4.4.2 Implications

As we discussed above, the shapes of the size distributions of C- and S-like asteroids are similar in the size range from several hundred meters up to about 10 km. This indicates collisional and dynamical behavior of C- and S-like asteroids are also similar for this size range. It has been analytically shown that one of the important factors for determining the shape of a size distribution in collision equilibrium is the size dependence of the impact strength (the

specific energy needed to disperse half of the target mass Q_D^*) and is insensitive to the size distributions of fragments produced in individual impacts (Dohnanyi 1969, Tanaka et al. 1996, O’Brien & Greenberg 2003, Kobayashi & Tanaka 2010). The similarity of their size distributions may reflect the common size-dependence of Q_D^* , which depends on material, internal structure, and impact velocity (Benz & Asphaug 1999, Jutzi et al. 2010), if asteroid population in this size range is under collision equilibrium. C-type and S-type asteroids are thought to have different bulk compositions (e.g., Nakamura et al. 2011, Usui et al. 2019, Potiszil et al. 2020, Kitazato et al. 2021). So, our results may indicate that differences in the bulk composition of asteroids hardly affect the size dependence of Q_D^* , at least in size range from several hundred meters to ten kilometers. This may indicate that most asteroids in this size range are rubble-piles, as represented by Itokawa and Ryugu.

It should be noted that rotational disruption induced by the YORP effect is not negligible at $D \lesssim 10$ km (Jacobson et al. 2014). Also, removal by the Yarkovsky effect somewhat affects the size distribution, while collisional disruption primary determines the size distribution of MBAs (O’Brien & Greenberg 2005). Similarity of the shapes of the size distributions of C- and S-like asteroids may indicate that these secondary effect hardly provide difference in size distributions for different spectral types.

4.4.3 Rough Estimate of the Total Number of MBAs

We can roughly estimate the total number of MBAs by combining the size distributions obtained in our work and previous works. In order to combine our results with those obtained in previous works, we converted the r -band magnitudes of our sample into the V -band magnitudes, assuming the average $m_V - m_r$ color of 0.25 mag based on the SDSS MOC4 data. Figure 4.10 shows the combined cumulative size distribution of all MBAs. The red and the black lines show our sample and those derived from the ASTORB database (Bowell et al. 1994), respectively. For reference, we plotted the slopes obtained by Ivezić et al. (2001), Gladman et al. (2009), and Peña et al. (2020) with the light-blue dashed line, the blue dot-dashed line, and green dotted line, respectively (thin lines represent extrapolations of derived distributions). We combined the size distribution of our sample with that of ASTORB at $H_V = 15.4$ mag, and the distributions obtained by Ivezić et al. (2001), Gladman et al. (2009), and Peña et al. (2020) are scaled so that they match that of ASTORB at $H_V = 13$, 15.5, and 15.5 mag, respectively, corresponding to the detection limit of each survey.

We found that the total number of MBAs brighter than $H_V = 20$ mag is estimated to be 8.6×10^6 , i.e., a couple of times as large as that obtained by extrapolating the results of Ivezić et al. (2001) or Gladman et al. (2009). We also found that the power-law slope of the absolute magnitude distribution at $H_V \simeq 13 - 17$ mag is nearly constant, which indicates that the break point found by the previous works may not be real. The potential reason for underestimating faint objects in the previous works is insufficient correction of detection bias. In our survey, the high sensitivity of the Subaru/HSC allowed high collection rate for faint objects. Also, we accurately corrected the number of detected asteroids considering the detection efficiency for each CCD image. It should be noted that the cumulative number of our sample at the combining point ($H_V = 15.4$ mag) with ASTORB has uncertainties of $+2.6 \times 10^4$ (25%) and -2.1×10^4 (20%), which produce uncertainties of $+2.1 \times 10^6$ and -1.7×10^6 for the above estimation of the total number of MBAs.

The fact that there are more small MBAs than previous estimate likely affects the esti-

mation of generation rates of near earth asteroids (NEAs) and meteorites. Also, our newly-obtained accurate size distribution can be used as a constrain on theoretical studies of collisional and dynamical evolution of asteroids (e.g., Bottke et al. 2005a,b, O'Brien & Greenberg 2005, de Elia & Brinini 2007). In particular, the size distribution of small MBAs is important for comparative studies of asteroids based on analysis of crater size distribution and estimate of the crater retention ages for those asteroids visited by spacecraft (e.g., Bottke et al. 2020).

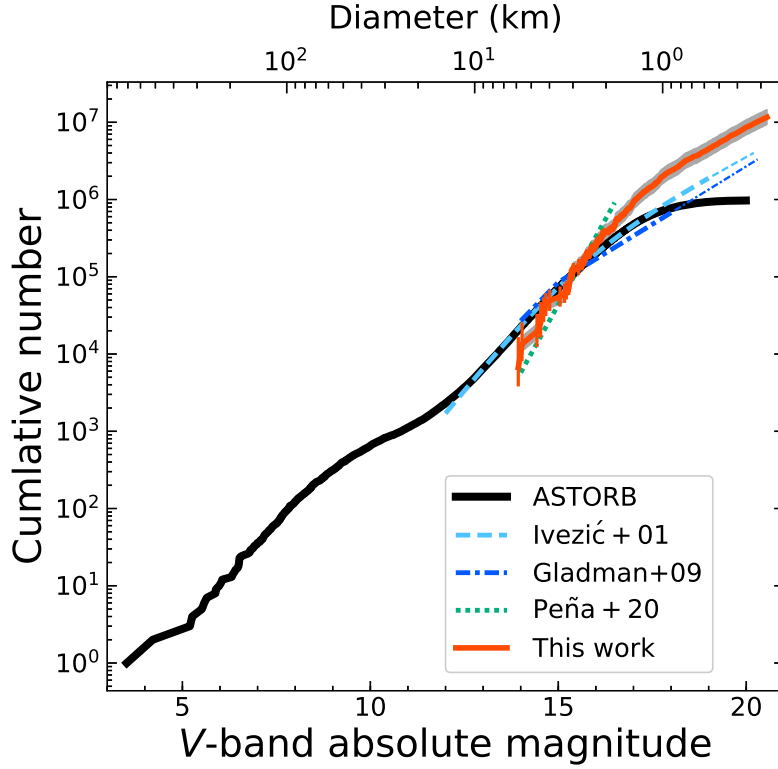


Figure 4.10: Cumulative size distributions of MBAs obtained from previous studies and the present work. The red line shows the distribution derived from our sample (vertical lines show error bars). The black line is derived from known asteroids based on the ASTORB database (Bowell et al. 1994). The light-blue dashed line, the blue dot-dashed line, and the green dotted line are drawn with the model slopes obtained by Ivezić et al. (2001), Gladman et al. (2009), and Peña et al. (2020), respectively, for reference (thin lines are their extrapolations). The ASTORB data are connected with our data at $H_V = 15.4$ mag (the gray area shows the error range produced by the uncertainty of the cumulative number at the connection point), with Ivezić et al. (2001) $H_V = 13$ mag, and with both Gladman et al. (2009) and Peña et al. (2020) at $H_V = 15.5$ mag, respectively. Diameters shown on the upper horizontal axis are obtained by converting from absolute magnitudes under the assumption of an albedo $p = 0.12$ (Usui et al. 2013).

Figure 4.11 shows the combined cumulative size distributions of C-type and S-type asteroids separately. We combined the size distributions of our C-/S-like sample with the known C-/S-type asteroids (taken from the ASTORB database, black solid line) by interpolating with the slope of all known asteroids (dotted lines) and blue/red asteroids of Ivezić et al. (2001) (dashed lines). Here, we converted the r -band magnitudes of our sample into

the V -band magnitudes using the average $m_V - m_r$ colors of 0.20 mag for the C-type and 0.28 mag for the S-type asteroids, respectively. We can roughly estimate that the total number of C- and S-type MBAs larger than 400 m in diameter are about 3.5×10^6 and 2.4×10^6 , respectively. Namely, the number of C-type asteroids is about 1.5 times as large as that of S-type asteroids for $D > 400$ m.

Yoshida & Nakamura (2007) found that the number ratio of C-like and S-like asteroids is 2.3 for $0.5 < D < 10$ km for the whole main-belt. Also, Ivezić et al. (2001) reported that the number ratio of blue and red asteroids is 2.3 for $D > 1$ km. Therefore, our result also shows a larger number of C-type asteroids than S-type, and is consistent with these previous works, although our result shows a smaller ratio. It should be noted that our ways of combining the size distributions have some uncertainties. First, the completeness limit of asteroids whose spectral type is obtained is uncertain, and actual size distributions in size range between the completeness limit of the known C-/S-type asteroids and bright end of the blue/red asteroids of Ivezić et al. (2001) are unknown, which can primarily affect the total number. Second, the cumulative numbers of our samples at the combining points with ASTORB have uncertainties of $+1.3 \times 10^4$ (30%) and -9.7×10^3 (23%) for C-like asteroids and $+2.2 \times 10^4$ (37%) and -1.6×10^4 (26%) for S-like asteroids. Also, our C-/S-like sample as well as the blue/red sample of Ivezić et al. (2001) likely contain asteroids with types other than the C-type and S-type. More spectroscopic or multi-band photometric observation of asteroids for a wide range of sizes is desirable to more accurately estimate the total number of asteroids with each spectral type.

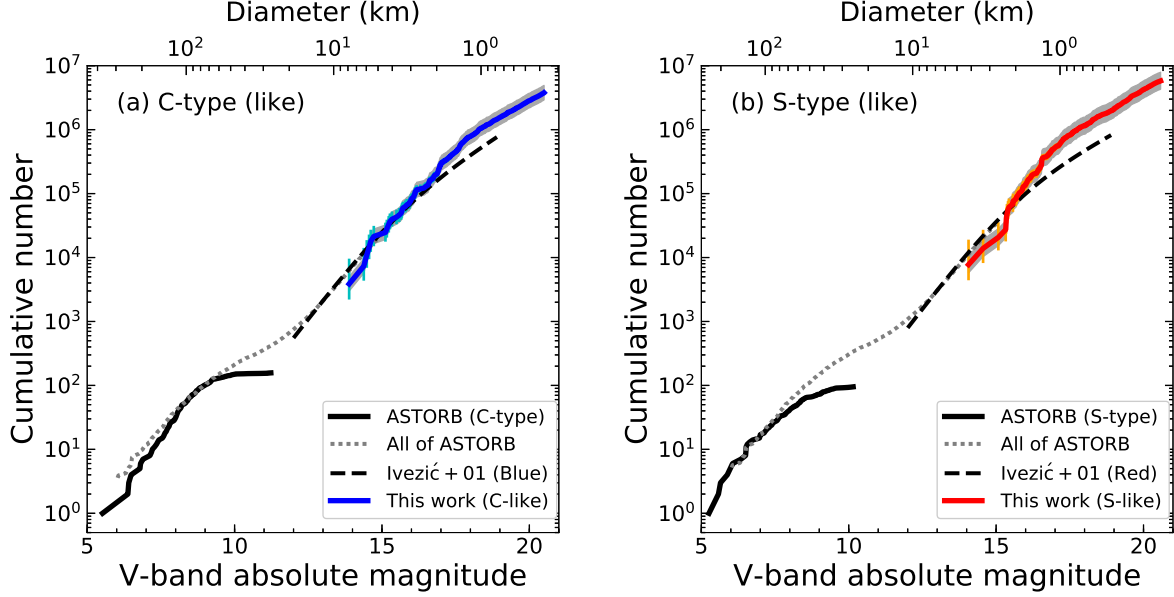


Figure 4.11: Cumulative size distributions of C-type and S-type MBAs obtained from previous studies and the present work. The size distributions of known C-/S-type asteroids (black solid line) are connected with those of smaller sizes using the slopes of all MBAs in the ASTORB database (dotted line) at $H_V = 9$ mag for C-type and $H_V = 7$ mag for S-type, respectively. The size distribution of all ASTORB MBAs is connected with the blue/red asteroids of Ivezić et al. (2001) (dashed line) at $H_V = 13$ mag. The size distributions of our C-/S-like asteroids are connected with the blue/red asteroids of Ivezić et al. (2001) at $H_V = 15.5$ mag, respectively (the gray area shows the error range produced by the uncertainty of the cumulative number at the connection point). Error bars represent Poisson's errors. Diameters on the upper horizontal axis are obtained by converting from absolute magnitudes under the assumptions of an albedo (a) $p = 0.07$ and (b) $p = 0.21$, which are the mean values for the C-/S-type MBAs, respectively (Usui et al. 2013).

4.5 CONCLUSIONS

We detected a large number of small MBAs in the g - and r -band images taken by the Hyper Suprime-Cam installed on the Subaru Telescope, and obtained an unbiased sample with a detection limit of $m_r = 24.2$ mag. We classified the sample by the $g - r$ color into two groups, bluish C-like and reddish S-like asteroids.

We found that the shapes of the size distributions of C-like and S-like asteroids agree well with each other for $0.4 < D < 5$ km. The similarity of their size distributions represents a similarity in collisional and dynamical behavior of C- and S-like asteroids for this size

range. Assuming the asteroid population is under collision equilibrium, the similarity of their size distributions may reflect the common size-dependence of the impact strength. This indicates that compositional difference hardly affects the size dependence of impact strength, at least for the above size range. This may indicate most asteroids in this size range are rubble-piles, represented by Itokawa and Ryugu.

By combining our results with previously known size distributions for larger asteroids, we found that the total number of MBAs brighter than $H_V = 20$ mag is a few times as large as that estimated by extrapolation of previous results. This would affect the estimation of the generation rates of NEAs and meteorites.

Chapter 5

Summary

In order to understand the formation and evolution of the solar system, it is necessary to understand the formation and evolution of giant planet and planetesimals (asteroids) with different compositions, such as NCs and CCs. The formation process of regular satellites around giant planets and observational estimates of the size distribution of asteroids can provide important information on these processes. In this thesis, in order to obtain constraints on the formation of giant planets and their regular satellites, we investigated the planetary-mass dependence of gas and dust accretion to the CPD (Chapters 2, 3). We also performed observational studies on the size distributions of S-like (NC) and C-like (CC) asteroids in the size range from 0.4 km to 5 km (Chapter 4).

In Chapter 2, we performed three-dimensional high-resolution hydrodynamic simulations in the local region around the protoplanet in the gas accretion phase. We investigated the planetary-mass dependence of radial/vertical distribution of source regions of streamlines that accrete onto the CPD (gas accretion band). We found that the radial width of the accretion band increases with increasing planetary mass and its planetary-mass dependence is different between the high-mass regime ($\gtrsim 0.2M_{\text{Jup}}$; assuming the MMSN with $a = 5.2$ au) and the low-mass regime ($\lesssim 0.2M_{\text{Jup}}$). We also found that the mass accretion rate onto the CPD is about 40% of that into the Hill sphere regardless of the planetary mass. We derived semi-analytical formulae of gas mass accretion rate onto the CPD by combining our results with the gap model obtained from global hydrodynamic simulations (Kanagawa et al. 2015). We found that the values of the accretion rates derived from our three-dimensional simulation are about 60% of those obtained from the two-dimensional case (Tanigawa & Tanaka 2016). In contrast, the planetary-mass dependence of the gas mass accretion rates remains the same between the two cases. The semi-analytical formulae obtained by our three-dimensional simulations can be used to improve models of giant planet formation.

In Chapter 3, we investigated the planetary-mass dependence of dust accretion onto the CPD by orbital integration of dust particles approaching the planet, considering the gas drag force using the gas field obtained in Chapter 2. Recent studies showed that one of the key parameters in satellite formation in the CPD is the mass fraction of solid particles in the gas accreting onto the CPD (the ratio of dust-to-gas accretion rates) (e.g., Shibaike et al. 2017). Thus, we focused on the degree of dust retention in accreting gas, which determines the ratio of dust-to-gas inflow rates, and we investigated its planetary-mass dependence using the numerical results and the semi-analytical approaches. The planetary-mass dependence

of the supply of satellite materials obtained by this work is helpful to the construction of satellite formation models (e.g., Shibaike et al. 2019).

Once the amount of supply of satellite material becomes clear, We can then proceed to development of more realistic models for the origin of their composition. For example, it is important to study the ice-to-rock ratio of the solid component accreting to the CPD to reproduce the current Galilean satellites. Information on the composition of the solid components accreting to the CPD is a key to understanding the spatiotemporal evolution of solar system formation, including the PPD structure in the late stage of the planet formation and the location and timing of giant planet formation. These are also related to understanding the factors contributing to the compositional dichotomy in the solar system seen in NCs and CCs, as described in Chapter 1. Numerical simulations of the capture of planetesimals into the CPD considering their composition have been performed recently (D’Angelo & Podolak 2015, Ronnet & Johansen 2020), but not for dust grains yet. The orbital integration of small dust particles requires hydrodynamical simulations that accurately resolve the temperature and density structures in the CPD, which is left as a future challenge.

In Chapter 4, we measured the size distributions of S-like (NC) and C-like (CC) asteroids using the observational data obtained by Subaru/HSC. We revealed the similarity of these two distributions in the size range from 0.4 to 5 km, which suggests a similarity in the collisional and dynamical behavior of NCs and CCs in this size range. This result may provide constraints on their implantation process into the main belt. Raymond & Izidoro (2017) showed that planetesimals scattered by growing giant planets in the gaseous disk could be naturally implanted into outer main belt, and the radial distribution of the planetesimals is consistent to that of CCs. If the process actually occurred in the primitive solar system, it is unlikely that the size distribution of CCs after implantation is similar to that of NCs, which could have undergone different formation and evolution processes, because the gas drag force depends on their size. In other words, the gas drag must be negligible for the implantation process of CCs, which would be an important constraint of the formation and evolution of the solar system.

As shown in this thesis, solving the puzzles of the formation and evolution of the solar system requires pieces from various approaches, including theoretical and observational studies as well as spacecraft exploration. The obtained picture of the formation and evolution of the solar system will lead to a universal understanding of the formation of planetary systems, including exoplanets.

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