DISTRIBUTION OF SMALL BODIES IN CIRCUMPLANETARY DISKS SUPPLIED FROM THE PROTOPLANETARY DISK.

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Introduction: The Galilean satellites have nearly coplanar and circular orbits and are thought to have formed in the circumplanetary gas disk (e.g., [1,2]). In order to clarify the timescale and radial location of satellite formation in the circumplanetary disk (CPD), understanding of the supply of building blocks of satellites is essential. Mainly two mechanisms have been considered so far as the supply of solids into the CPD: capture of solid bodies by the disk due to gas drag (e.g., [3]), and delivery with the gas inflow onto the CPD [1]. If the giant planet is not isolated from the reservoir of solids in the protoplanetary disk, planetesimals that are large enough to be decoupled from the gas can be captured in the high-density region of the CPD in the vicinity of the planet [3,4]. Orbits of the captured planetesimals are gradually circularized while drifting inward slowly, and they would pile up in the region corresponding to the current locations of regular satellites [4]. However, if the giant planet opens a gap in the protoplanetary disk, assistance by Saturn would be needed for the delivery of solids into the CPD [5]. On the other hand, small particles can be delivered into the CPD coupled to the inflowing gas. Such small bodies often called pebbles may have played an important role in satellite formation [6-8].

For the supply of such small bodies into the CPD, the gas flow outside of the planet's Hill sphere is also important. The gas flow around giant planets has been examined by hydrodynamic simulations (e.g., [9,10]). These studies have shown that most of gas flows onto the CPD in the vertical direction from the protoplanetary disk. Such gas flow may prevent accretion of small particles initially confined in the midplane of the protoplanetary disk into the CPD [11]. However, small particles are likely stirred off the midplane by turbulence. Therefore, effects of the gas flow around the planet on small particles vertically distributed in the protoplanetary disk need to be clarified for a better understanding of the supply of building blocks of regular satellites.

In the present work, we examine accretion of solid particles onto CPDs from the protoplanetary disk by orbital integration. In order to take account of effects of the gas flow around a growing giant planet, we directly use results of high-resolution hydrodynamic simulation in our orbital integration.

Model: We numerically solve the equations of motion for the three-body problem for the Sun, the planet, and a particle, taking account of the gas drag from the inflowing gas. We assume that a growing giant planet is embedded in the protoplanetary disk and its orbit is circular in the midplane of the disk. Gas drag force on the particle is calculated using the distribution of the density and velocity of the gas obtained by hydrodynamic simulation [9,10]. Figure 1 shows the distribution of the gas flow used in the present study. Sufficiently small particles well coupled to the gas are supplied with the vertically inflowing gas onto the CPD.

We assume that the particles are spherical and their bulk density is 1g cm^{-3}. In order to focus on the effect of the vertical distribution of particles in the protoplanetary disk, we assume that initial eccentricity of the particles is zero. Therefore, parameters of the particles are as follows: the particle radius r_s, the difference in the semi-major axes of the planet and the particle, the vertical phase angle of the particles, and the initial vertical position of the particles. When we begin orbital integration of sufficiently small particles from a certain vertical position above the midplane, they stay above the midplane until they approach the planet. For such a case, we set their initial vertical position as one of their initial conditions, assuming that the vertical component of their initial velocity is zero. When bodies are sufficiently large to become at least partly decoupled form the gas, they undergo vertical oscillation across the midplane of protoplanetary disk before approaching the planet. In such a case, we give initial orbital inclination and vertical phase angle as parameters. We stop orbital integration when any one of the following conditions is met,: (1) the particle collides with the planet, (2) the distance between the particle and the planet becomes sufficiently large again, (3) the particle's orbit becomes planet-centered and nearly circular in the CPD, or (4) the particle is captured within the planet's Hill sphere and orbits around the planet many times.

Results: Figure 2 shows the radial and vertical locations of bodies at the time of their capture in the CPD. We find that these distributions can be roughly divided into three groups depending on the size of particles. In the case of 1 m particles, their locations at the time of capture are distributed over wide radial regions

near the midplane of the CPD. Particles with such a size undergo vertical oscillation before approaching the planet, and penetrate the CPD in the vertical direction. Then, when they go through the dense part of the CPD, a sufficient amount of kinetic energy is lost, and become captured eventually. After their capture, their orbits gradually settle toward the midplane.

Although 10 cm particles also exist near the midplane, all of them are captured at the outer edge of the CPD. This is approximately the critical size for vertical oscillation. Therefore, regardless of the initial vertical positions, particles with that size settle down near the midplane and enter the planet's Hill sphere almost from the midplane. After that, their energy is gradually dissipated due to gas drag, and become captured while orbiting about the planet. Because the above picture of capture is independent of their initial vertical positions, the locations of 10 cm particles at the time of capture are almost the same.

On the other hand, we find in Figure 2 that 1 mm and 1 cm particles are vertically distributed in the CPD at the time of capture. These small particles are supplied into the CPD with the help of vertically accreting gas. Thus, their vertical distribution reflects the structure of the accreting gas flow. Their vertical positions become higher with increasing radial distance from the planet, reflecting the vertical structure of the CPD (see the lower panel of Figure 1). These small particles are expected to settle down to the midplane before they become part of forming satellites in the CPD. Thus, our results have an important implication for the radial location of the onset of satellite accretion.

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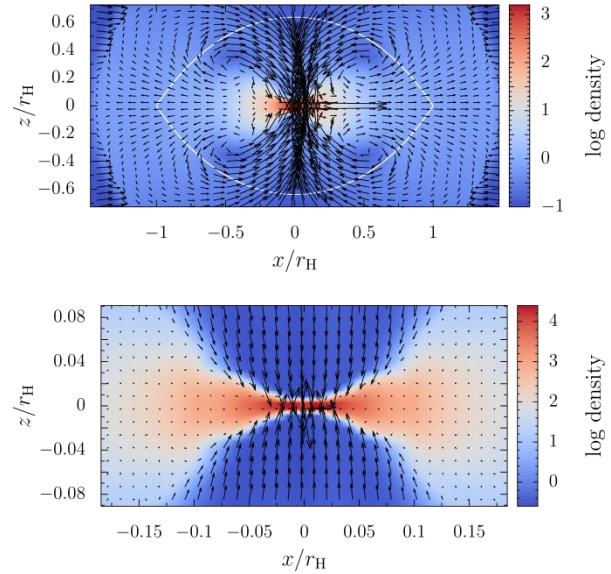

Figure 1: Distribution of log density (colors) and velocity (arrows) of the gas obtained by high-resolution hydrodynamic simulation. A planet with mass of about 0.4 Jupiter mass is located at the origin, corresponding to 5 au from the Sun. The distance is scaled by the planet's Hill radius and the white line in the upper panel shows Hill sphere. The lower panel is a blow-up of the upper panel.
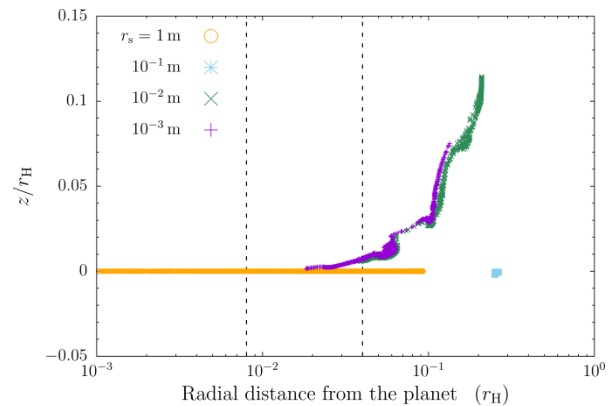

Figure 2: Distribution of captured particles in the circumplanetary disk. Particles are initially distributed vertically in the protoplanetary disk from the midplane up to the Hill radius of the planet. Marks with different colors show results with different sizes of particles. The two vertical dashed lines represent the current radial locations of Io and Callisto (in units of Jupiter's Hill radius), respectively.