Accretion of vertically stirred small bodies in the protoplanetary disk onto circumplanetary disks.

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Introduction: Gas giant planets such as Jupiter and Saturn have many satellites around them. Understanding of the origin of these satellite systems would also help our understanding of the formation processes of the giant planets. The principal regular satellites such as the Galilean satellites or Titan are thought to have formed by accretion of solid bodies in the circumplanetary gas disk (e.g., [1,2]). In this case, solid bodies that are supplied into the circumplanetary disk become building blocks of the regular satellites. Therefore, their size as well as the amount and radial distribution in the circumplanetary disk are important in determining the radial locations and formation timescale of the regular satellites [3]. Furthermore, since those sloid bodies that are not accreted into satellite ultimately accrete onto the host planet, the supply of solid bodies onto the cicumplanetary disk is also important in understanding the origin of the abundance of heavy elements in the atmospheres of gas giant planets.

When the size of solid bodies delivered from the protoplanetary disk is sufficiently small, their motion is coupled to the accreting gas, thus those particles coupled to the gas accreting within the planet's Hill sphere are delivered into the circumplanetary disk [1]. On the other hand, sufficiently large bodies that are decoupled from the accreting gas can be captured within the planet's Hill sphere, if they pass through the sufficiently dense part of the circumplanetary disk in the vicinity of the planet [4-6]. Bodies with an intermediate size between the above two extremes suffer drag force from the complicated gas flow near and within the planet's Hill sphere. In order to understand the process of accretion of solid bodies in such cases, orbital integration of bodies under the influence of such complicated gas flow is required. For example, when the solid bodies are assumed to be initially confined within the planet's orbital plane, numerical simulations show that the rate of accretion into the planet's Hill sphere becomes the largest for bodies with radius of about 10 m [7].

On the other hand, high-resolution simulations of gas flow onto a growing giant planet revealed detailed structures of the accreting gas and circumplanetary disk (e.g., [8,9]). These simulations show that most of gas accretion onto the circumplanetary disk occurs nearly vertically. If there are a large amount of sufficiently small solid bodies (i.e., pebbles [10]) in the protoplanetary disk and they are vertically stirred by turbulence, such vertically accreting gas flow would significantly influence the accretion process of solid bodies into the planet's Hill sphere. Also, pebbles accreted into the circumplanetary disk would play an important role in satellite accretion [11].

In the present work, taking account of the gas flow obtained by high-resolution hydrodynamic simulation, we perform orbital integration of small bodies under the influence of gas flow accreting onto a growing giant planet, and examine accretion of solid bodies vertically stirred in the protoplanetary disk into the planet's Hill sphere.

Model: We assume that a growing giant planet is moving on a circular orbit in the protoplanetary disk with a fixed orbital radius. We deal with the three-body problem for the sun, the planet, and a particle. In order to examine the motion of particles around the planet, we use Hill's equation with gas drag term. In calculating the gas drag, we interpolate the distributions of density and velocity of the gas obtained by hydrodynamic simulation [5-7]. Figure 1 shows the velocity and density of the gas used in the present work. Although the distribution is nearly axisymmetric in the vicinity of the planet, we can see that the use of results of hydrodynamic simulation is necessary to accurately take account of the drag force from the accreting gas flow.

We integrate the orbits of particles with various radii (r_s) by solving Hill's equation, using the eighth-order Runge-Kutta integrator. Initially, particles are placed above the midplane of the protoplanetary disk. Initial eccentricity of particles was set to zero in order to focus on the effect of the vertical distribution of the particles in the protoplanetary disk. When the size of the particle is sufficiently small, it stays above the midplane until it approaches the planet. On the other hand, in the case of large particles that are decoupled from the gas flow, they undergo vertical oscillation across the midplane as they approach the planet, and their efficiency of capture within the planet's Hill sphere depends on the initial phase of the vertical motion. Thus, in the latter case, we vary the initial phase angles and obtain the accretion rate by averaging over the angles. We stop the integration when one of the following conditions is met: (1) when the particle collides with the planet, (2) when the distance between the particle and the planet becomes large again, (3) when the planet-centered orbit of the particle becomes circularized in the circumplanetary disk or (4) when the particle is gravitationally captured within the planet's Hill sphere and orbits about the planet for many times.

Results: Figure 2 shows the rate of capture within the planet's Hill sphere (solid lines) and that of collision with the planet (dashed line). In the case of particles initially confined within the midplane, those particles with sufficiently small sizes, $r_s \leq 10^{-2}$ m, cannot be captured within the planet's Hill sphere, and the accretion rate takes on the maximum value at $r_s =$ 10 m, as shown by the previous work [7]. This is because the gas in the protoplanetary disk in the midplane cannot enter the Hill sphere [7,9]. On the other hand, when the particles are initially placed above the midplane, even such small particles with $r_s \leq 10^{-2}$ m can become captured within the planet's Hill sphere. In other words, small particles that cannot accrete onto the circumplanetary disk when they are initially confined in the midplane can accrete with the help of the vertically accreting gas. When the particle radius is equal to 10 cm, capture rates are nearly the same regardless of the initial inclination. This is because the relatively weak gas drag leads the orbits of the particles to settle toward the midplane while they approach the planet. On the other hand, in the case of sufficiently large particles with $r_s \geq 10$ m, we find that capture rates decrease with increasing initial inclination or particle radius. This is because the efficiency of capture by the planet becomes lower due to the large amplitude of the particles' vertical oscillation or insufficient gas drag.

Our results suggest that vertical stirring of particles in the protoplanetary disks would be important for the supply of solid particles onto the circumplanetary disks, especially when a significant amount of small particles are vertically stirred above the midplane, with vertical scale height of the particles comparable to or larger than the planet's Hill radius.

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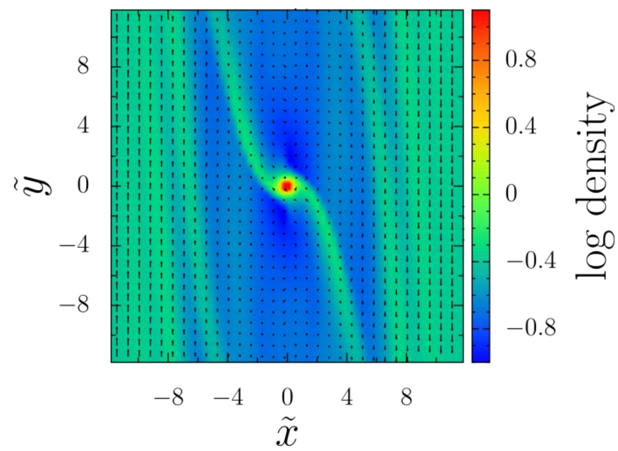

Figure 1: Distribution and motion of the gas in the vicinity of a Jupiter-mass planet at 5au from the Sun, obtained by high-resolution hydrodynamic simulation. The planet is at the origin, and the distance is scaled by the planet's Hill radius. The colors represent the logarithmic gas density in the mid-plane, and the arrows indicate the velocity distribution.

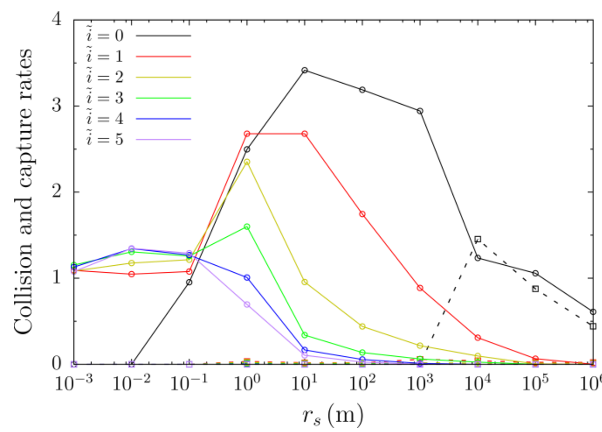

Figure 2: Non-dimensional accretion rates of solid bodies within the planet's Hill sphere, as a function of the size of particles, r_s. Solid lines represent the rates of capture within the Hill sphere due to gas drag. Lines with different colors show results with different initial height of the particles scaled by the planet's Hill radius. Dashed line shows the rates of collision with the planet.