EFFECT OF ABLATION ON CAPTURE OF PLANETESIMALS BY GAS DRAG FROM CIRCUMPLANETARY DISKS

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Introduction: Giant planets capture gas and solid particles from protoplanetary disk by their gravity, and circumplanetary disks are formed around them. The regular satellites of the giant planets (e.g. Galilean satellites) have nearly circular and coplanar prograde orbits, and are thought to have formed by accretion of solid particles in the circumplanetary disk [e.g. 1, 2]. Because a significant amount of gas and solids are likely to be supplied to growing giant planets through the circumplanetary disk, the amount of solid material in circumplanetary disks is important not only for satellite formation but also for the growth and the origin of the heavy element content of giant planets.

Solid particles smaller than meter-scale are strongly coupled with the gas flow from the protoplanetary disk and delivered into the disk with the gas. On the other hand, trajectories of large planetesimals are decoupled from the gas. When these large planetesimals approach a growing giant planet, their orbits can be perturbed by gas drag from the circumplanetary disk depending on their size and random velocity, and some of them would be captured by the disk.

In our recent work, we examined the capture of planetesimals by gas drag from circumplanetary disks and found that it occurs for sufficiently large values of gas drag parameter \( \zeta \), which depends on planetesimal radius of planetesimals and surface density of the disk. We also found that there are two types of capture: prograde (i.e. trajectories in the same direction as the circular motion of the gas) and retrograde trajectories. Since gas drag in the case of retrograde trajectories is larger than that of the prograde case, capture rate of the retrograde case are also larger. However, when planetesimals pass through the gas disk, mass loss of planetesimals due to by ablation may occur [e.g., 2, 3]. If the mass of planetesimals significantly changes due to ablation, the strength of gas drag force exerted on them also changes and alters capture rates. This mechanism may also contribute to the supply of solids into circumplanetary disks [2].

In the present work, we examine changes of capture rate and mass of planetesimals, taking account of both gas drag and ablation.

Method: We deal with the three-body problem for the sun, a planet, and a planetesimal, and assume that the planet has a circumplanetary gas disk. The radial distribution of the gas density is assumed to be given by a power-law, and its vertical structure is assumed to be isothermal. Gas element in the disk are assumed to rotate in circular orbits around the planet, with an angular velocity slightly lower than Keplerian velocity due to its radial pressure gradient. The initial azimuthal distance between planetesimals and the planet is taken to be large enough to neglect their mutual gravity. We stop our calculation when one of the following conditions is met [4]: (i) the distance between the planet and the planetesimal becomes large again, (ii) the planetesimal’s energy becomes less than zero and gravitationally bound to the planet. The strength of gas drag is expressed in terms of a non-dimensional parameter \( \zeta \) [4]. Therefore, we can examine capture of planetesimals with various sizes by the gas disk with various densities (for example, corresponding to various stages of dispersal of the disk), from results of orbital integration with various values of \( \zeta \).

In the formulation of the present work, the mass of planetesimals \( m_s \) is included in \( \zeta (\propto m_s^{-2/3}) \). Thus, we investigate time evolution of the position and velocity or planetesimals and \( \zeta \) simultaneously. We integrate Hill’s equation including the gas drag term with various initial orbital elements and \( dc/dt \), using the eighth-order Runge-Kutta integrator. Energy of planetesimals decreases by gas drag when they pass through the disk. We turn on gas drag and ablation only within the planet’s Hill sphere. When the energy of a planetesimal becomes less than zero within the planet’s Hill sphere, it is regarded as becoming captured by the circumplanetary disk.

Results: First, we investigate relative difference in capture rates between the cases with and without ablation in the mid-plane (Figure 1). \( e \) is the eccentricity of planetesimals and \( h_H = \{(M+m_s)/M_\odot\}^{1/3} \) (\( M \) and \( M_\odot \) are masses of planet and sun, respectively). When \( e/h_H < 3 \), the difference is less than 5% both in the prograde and retrograde cases, and the effect of ablation seems negligible. When \( e/h_H > 3 \), the difference becomes notable, and we find that the effect of ablation in the retrograde case is more notable than in the prograde case, since the relative velocity between planetesimals and the gas is larger. However, even in this case, the difference is \( \sim 30\% \) at most. Considering that we have used...
a rather (probably unrealistically) large value of the ablation coefficient $\sigma$ following [5], we can conclude that the effect of ablation on capture rates is insignificant.

Although ablation does not seem to affect capture rates of planetesimals significantly, the degree of mass loss (or size change) of planetesimals due to ablation during their passage through the circumplanetary disk is important in understanding the process of supply of solids to the planet and the circumplanetary disk. Figure 2 shows the values of $\zeta$ relative to its initial value $\zeta_0$, at the end of orbital integration (i.e., when the condition (i) or (ii) is met), as a function of the planetesimals' minimum approach distance to the planet. Panels (a) and (b) show the cases with $e/h_H = 1$ and 10, respectively. In both panels, we find that $\zeta$ increases significantly, due to mass loss by ablation. We can see that the change in $\zeta$ depends on $\zeta_0$ only weakly, while it strongly depends on planetesimals’ eccentricity. This is because $d\zeta/dt$ is proportional to $u^3$, where $u$ is the velocity of the planetesimal relative to the gas, and $\zeta$ of planetesimals with large eccentricity (i.e., large relative velocity) increases (and their mass decreases) significantly through the interaction with the gas until they become captured. Thus, although the effect of ablation on the capture rate is not significant, mass loss of planetesimals due to ablation may be significant, especially for those with large random velocity. In this case, when such initially large planetesimals are captured by the circumplanetary disk, they would supply solids to the planet and/or the circumplanetary disk in a form of much smaller bodies than their original sizes.

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