CAPTURE OF PLANETESIMALS BY 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 [e.g. 3]. 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 the present work, we examine orbital evolution of planetesimals approaching a growing giant planet with a circumplanetary disk, and evaluate the capture probability.

Method: Less massive growing protoplanets in the solar nebula are likely to have atmospheres whose density distribution is nearly spherically symmetric, and capture of planetesimals by gas drag for such atmospheres have been examined by previous studies [e.g. 4-6]. In the present work, we study capture of planetesimals by a circumplanetary gas disk in a way similar to [6]. 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. We turn on gas drag only within the planet's Hill sphere [6]. 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 [6]: (i) the distance between the planet and the planetesimal becomes large again, (ii) the planetesimal hits the planet, (iii) 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 ζ, which is a function of gas surface density and the radius of planetesimals [6]. Therefore, we can discuss 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 ζ. We integrate Hill's equation including the gas drag term with various initial orbital elements, using the eighth-order Runge-Kutta integrator.

We consider the following two types of capture: (i) when planetesimals hit the planet, regardless of whether they lose enough energy to become gravitationally bound, (ii) when planetesimals lose enough energy through gas drag and become gravitationally bound within the planet's Hill sphere [6]. Rates of direct collision onto protoplanets in the gas-free environment have been obtained analytically when the random velocity of planetesimals is large enough, and numerically in more general cases. Here, we mainly focus on the capture in the case of (ii).

Results: Energy of planetesimals decreases by gas drag when they pass through the disk. Energy dissipation in the case of prograde trajectories (i.e. trajectories in the same direction as the circular motion of the gas) are different from that of retrograde trajectories. Since the relative velocity between planetesimals and the gas in the case of retrograde trajectories is larger than that of the prograde case, gas drag is stronger and thus energy of planetesimals is dissipated more quickly in the case of retrograde trajectories. When planetesimals move in the mid-plane of the circumplanetary disk, energy dissipation during one encounter with the planet can be obtained analytically, using the fact that the energy is reduced due to gas drag mostly when the planetesimal passes through the densest part (i.e. inner part) of the disk. That is, we can estimate the energy dissipation for a given approach minimum distance of planetesimals to the planet. If planetesimal's random velocity is small, the effect of the gravity of the sun and the planet are both important.

In such a case, we assume that the trajectory is a parabola whose focus is at the planet's center and the distance from the planet at pericenter is regarded as the minimum distance. If the random velocity is large enough, on the other hand, we assume that planetesimals follow the unperturbed heliocentric orbits, because we can neglect gravitational interaction with the planet. We obtain an analytic expression for energy dissipation during a prograde or retrograde encounter based on the results for the above two limiting cases, and find that they agree well with results of orbital integration. In the case of inclined orbits relative to the mid-plane of the disk, energy dissipation is more complicated because planetesimals' trajectories pass through the disk in various ways.

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. The distance from the planet within which a planetesimal can become captured depends on the energy of the planetesimal before encounter; planetesimals with large initial energy cannot become captured unless they pass through the dense, inner part of the disk. We define the effective capture radius $R_{\rm c}$ by the distance from the planet at which the energy dissipation equals to the initial energy of a planetesimal [6]. That is, planetesimals with a given size become captured by gas drag when they encounter the planet with minimum approach distance smaller than $R_{\rm c}$. We obtained an analytic expression for $R_{\rm c}$ in the case of the coplanar case (Fig. 1).

We also obtained capture probabilities of planetesimals with given initial orbital elements by replacing the planet's physical radius in the analytic expression of collision rates with the above effective capture radius. If we assume a uniform distribution of planetesimals' orbital phase angle, prograde and retrograde encounters are expected to occur with an equal probability. In fact, our numerical results are consistent with the above analytic results. We will discuss results of orbital integration for capture rates, including the cases of inclined orbits of planetesimals.

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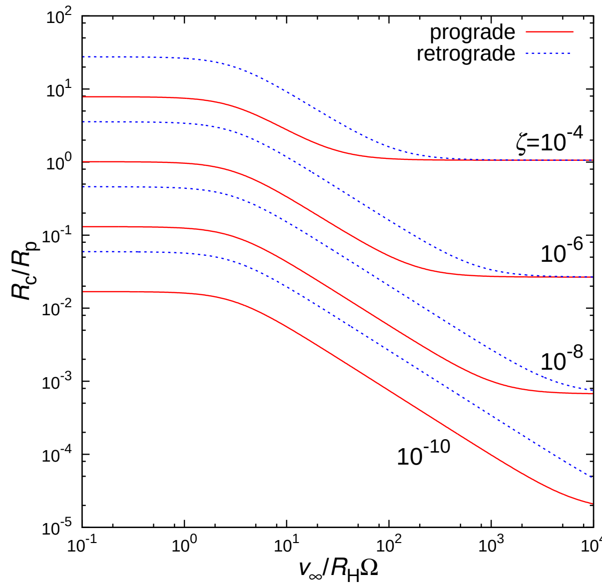

Figure 1: Effective radius for capture $R_{\rm c}$ in units of the planet's physical radius $R_{\rm p}$ as a function of planetesimal's heliocentric random velocity v_∞ scaled by $R_{\rm H}\Omega$, where $R_{\rm H}$ is the planet's Hill radius and Ω is the planet's orbital angular frequency. Solid lines show the case of prograde trajectories and dashed lines show the case of retrograde ones. Four sets of lines correspond to the cases with $\zeta = 10^{-4}, 10^{-6}, 10^{-8}, 10^{-10}$, respectively from top to bottom.

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