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Capture of planetesimals by circumplanetary disks

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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. 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 the present work, we examine orbital evolution of planetesimals approaching a growing giant planet with a circumplanetary disk, and evaluate the capture probability.

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 elements 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. We integrate Hill's equation including the gas drag term with various initial orbital elements. 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. Here, we mainly focus on the capture in the case of (ii).

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 because the relative velocity between planetesimals and the gas in the case of retrograde trajectories is larger than that of the prograde case. When planetesimals move in the mid-plane of the circumplanetary disk, energy dissipation of each case during one encounter with the planet can be obtained analytically. We 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. We define the effective capture radius R_c by the distance from the planet at which the energy dissipation equals to the initial energy of a planetesimal. We obtained an analytic expression for R_c and capture probabilities of planetesimals with given initial orbital elements in the coplanar case. We will discuss results of orbital integration for capture rates, including the cases of inclined orbits of planetesimals.

Keywords: circumplanetary disk, gas drag, satellite