Orbital evolution of planetesimals in circumplanetary gas disks and probability of collision with protosatellites.

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Introduction: In the late stage of the formation of giant planets, sufficiently massive proto-giant planets capture gas and solids from the protoplanetary disk and form circumplanetary disks. Regular satellites of the giant planets such as the Galilean satellites of Jupiter are orbiting in the prograde direction in approximately circular and co-planer orbits, thus they are thought to be formed in the circumplanetary disks. Regular satellites account for most of the total mass of a satellite system. Therefore, in order to understand the processes of the formation of satellite systems around giant planets, clarification of the formation processes of regular satellites is essentially important. In the present work, we focus on the orbital evolution of solid bodies, which we call planetesimals, in circumplanetary gas disks.

Orbital decay of planetesimals is caused by different mechanisms depending on their sizes. When planetesimals are small, aerodynamic gas drag is dominant. Sufficiently small bodies are coupled to the gas and would be supplied to the circumplanetary disks with the inflowing gas [1, 2]. Planetesimals that are large enough to become decoupled from the motion of the gas can be captured by gas drag from the circumplanetary gas disk [3]. In the latter case, the gas drag becomes weaker with increasing size of planetesimals [4]. On the other hand, the so-called type-I migration due to gravitational interaction with the circumplanetary gas disks becomes dominant for massive bodies [e.g., 1, 2, 5, 6]. While the type-I migration is essentially important in the late stage of satellite formation, orbital evolution by aerodynamic gas drag governs the orbital evolution of small solid bodies supplied from the protoplanetary disk to the circumplanetary disks. Dynamical evolution of such small bodies in the circumplanetary gas disks is also important for the growth of protosatellites.

Previous studies assumed that the major building blocks of regular satellites are relatively small solid particles supplied into circumplanetary disks with the inflowing gas [1, 2]. Recently, it has been shown that the efficiency of capture of planetesimals from their heliocentric orbits by gas drag from the circumplanetary disk is the highest for planetesimals with radii of 10-100m [7]. However, orbital evolution of captured planetesimals in circumplanetary gas disks and their contribution to the growth of satellites are not well understood. In the present work, we examine orbital evolution of planetesimals in circumplanetary gas disks, and the probability of capture of such small bodies by a growing protosatellite.

Model: We assume that a relatively large protosatellite is moving on a circular orbit in the circumplanetary disk with a fixed orbital radius, and that small bodies undergo orbital decay due to gas drag in the circumplanetary gas disk. We deal with the three-body problem for the central proto-giant planet, a protosatellite, and planetesimals, neglecting gravitational interactions among planetesimals. We also assume that the circumplanetary gas disk is axial symmetry and geometrically thin, and that its vertical structure is isothermal. In the final stage of the formation of giant planets, the timescale of gas inflow from the protoplanetary disk can be expected to be long compared to the timescale of viscous evolution of the disk, because of the dissipation of the protoplanetary disk or opening of a gap by the planet. In such a stage, the circumplanetary disk can be assumed to be in the quasi-steady-state, where the inflow of the gas and its viscous diffusion are balanced [1]. Also, the temperature of such a disk is determined by the balance between viscous heating and radiative cooling from the disk surface. Under these assumptions, the radial distribution of the gas surface density and sound velocity can be given as $\Sigma \propto r^{-3/4}$ and $c_\mathrm{s} \propto r^{-3/8}$, respectively [1, 8]. Gas elements in the disk are assumed to be moving on circular orbits around the planet, with the velocity slightly slower than the Keplerian velocity due to the radial pressure gradient.

Initially, 1000 planetesimals are placed on circular and non-inclined orbits exterior to the orbit of the protosatellite. We examine the probability of collision with the protosatellite of planetesimals that undergo orbital decay due to gas drag. We examine cases of different sizes of planetesimals, in order to see effects of varying the strength of gas drag exerted on planetesimals on the collision probability. On the other hand, because the protosatellite is sufficiently large compared to planetesimals, the effect of gas drag on the protosatellite is rather weak. Hence, we ignore the orbital decay of the protosatellite. We integrate the equation of motion including the gas drag term using the fourth-order Hermite integrator.

Results: We numerically evaluate the probability of collision of migrating planetesimals with the protosatellite, and its dependence on the size of planetesimals. When planetesimals are sufficiently small to be coupled with the gas, the complicated flow pattern of the inflowing gas needs to be taken into account [7]. Here, we focus on large planetesimals that are decoupled from the gas, assuming that their radius is $r_\mathrm{p} \geq 10$ cm. We also set the mass and semi-major axis of protosatellite to be $m_\mathrm{s} = 10^{24}$ g and $a_\mathrm{s} = 20R_\mathrm{J}$ (R_J is the current radius of Jupiter), respectively.

Figure 1 shows the probability of collision with the protosatellite as a function of the size of planetesimals. We find that the collision probability has a peak at a certain size. This is because the time scale of the orbital decay varies depending on the size of planetesimals. We can see that the collision probability is extremely low when planetesimals are sufficiently small ($r_\mathrm{p} \leq 1$m). In this case, orbital decay of planetesimals is so rapid that they migrate inward across the orbit the protosatellite before experiencing close encounters with it. The time scale of orbital decay of planetesimals is shorter than the synodic period with the protosatellite, thus most of planetesimals pass through the orbit of protosatellite without undergoing collision. The time scale of orbital decay becomes longer with increasing size of planetesimals. When the decay speed is sufficiently slow, planetesimals stay in the vicinity of the protosatellite for a sufficiently long period of time, and experience gravitational scattering by the protosatellite. In this case, the probability of collision with the protosatellite increases, owing to the gravitational attraction by the protosatellite. As a result, the collision probability takes on the maximum value at $r_\mathrm{p} \sim 25$ m. When the size of planetesimals becomes still larger, the probability of collision decreases rapidly. This is because planetesimals are captured into mean motion resonances with the protosatellite and cannot approach the orbit of the protosatellite. Since the orbital decay is sufficiently slow, orbital eccentricities of planetesimals are excited as they migrate inward across the resonance positions with the protosatellite. Eventually, the orbital decay of such large planetesimals stops when they are captured into one of the mean motion resonances in the vicinity of the orbit of the protosatellite. We also examined cases of various masses and semi-major axes of the protosatellite, and obtained similar results.

Our results suggest that planetesimals in a certain range of sizes preferentially collide with growing protosatellites. That is, growing protosatellites in circumplanetary gas disks would preferentially accrete solids bodies in a certain range of sizes. This needs to be taken into account in models of satellite accretion.

References: [1] Canup, R. M., & Ward, W. R., 2002, AJ, 124, 3404; [2] Canup, R. M., & Ward, W. R., 2006, Nature, 441, 834; [3] Fujita, T., Ohtsuki, K., Tanigawa, T., & Suetsugu, R., 2013, AJ, 146, 140; [4] Adachi, I., Hayashi, C., & Nakazawa, K., 1976, Prog. Theor. Phys., 56, 1756; [5] Gorldreich, P., & Tremaine, S., 1980, ApJ, 241, 425; [6] Ward, W. R., 1986, Icarus, 67, 164; [7] Tanigawa, T., Maruta, A., & Machida, M. N., 2014, ApJ, 784, 109; [8] Ogihara, M., & Ida, S., 2012, ApJ, 753, 60

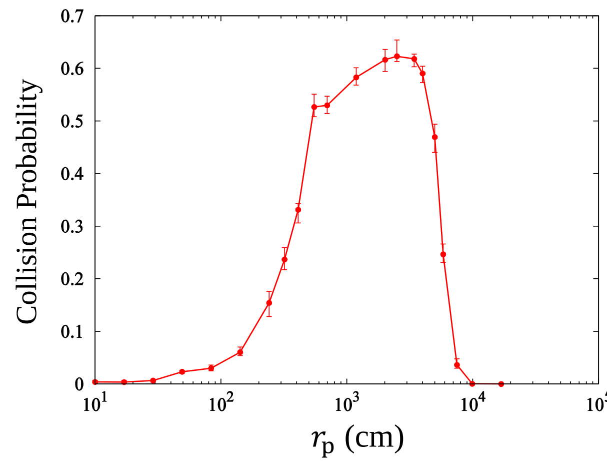

Figure 1: Collision probability of migrating planetesimals with a protosatellite in the circumplanetary gas disk, as a function of the size of planetesimals, r_p. Results for the case of a protosatellite with mass $m_\mathrm{s} = 10^{24}$ g, and semi-major axis $a_\mathrm{s} = 20R_\mathrm{J}$ are shown. Calculations for each case were performed five times by changing the initial distribution of planetesimals and the mean values of the collision probability are shown, because the probability slightly varies when the initial positions of planetesimals are varied. The maximum and minimum values for each case are represented by the error bars.