Evolution of circumplanetary particle disks and formation of multiple-satellite systems

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Introduction: Most of the planets in the solar system have satellite systems around them. In systems with a single satellite such as the Earth-Moon or Pluto-Charon system, satellite mass is relatively high compared to the host planet's mass (M_s/M_c~0.012, M_s/M_c~0.1 respectively, where M_s and M_c are the mass of satellite and central planet). On the other hand, giant planets such as Jupiter, Saturn and Uranus have multiple-satellite systems. Generally, their inner major satellites exist outside their Roche limit with substantial mass ratio M_s/M_c~10^{-4}-10^{-5}. Those inner satellites are on nearly circular prograde orbits with low inclinations, and they are called regular satellites.

Formation of large regular satellites of Jupiter and Saturn has been explained by accretion in a circumplanetary gas disk [e.g., 1,2]. On the other hand, it has been recently shown that systems of regular satellites of Saturn, Uranus and Neptune can be formed from a circumplanetary particle disks within the Roche limit [3]. Formation of satellites from a circumplanetary particle disk within the Roche limit was first studied in the context of lunar formation [e.g., 4,5]. Initially, particles are distributed within the Roche limit a_R and their accretion is prohibited. Then, the disk spreads with time. The disk evolution is regulated by its viscosity and the viscosity is regulated by spiral patterns, which develop in the disk by gravitational instability [6]. As the disk spreads and the disk materials diffuse beyond the Roche limit, the materials start to form gravitationally bound aggregates [4,5].

In the case of relatively massive disk, a large single satellite such as Moon or Charon is its outcome [4,5]. However, if the initial disk is less massive, the viscosity of the disk is low and the time scale of disk diffusion is much longer. In this case, a satellite formed at the disk edge is less massive and migrates outward by large distance through the interaction between the disk. In addition, when the first satellite migrates outward by large distance, a significant amount of disk mass still remains. Thus, the satellite formation process in less massive disks is different from the lunar formation process [3,7]. Crida and Charnoz [3] developed an analytic model for the formation of multiple satellites from a circumplanetary particle disk, with the assumption that the mass flow through the Roche limit is constant. Their model successfully explains the characteristics of the masses and orbits in the satellite systems of Saturn, Uranus and Neptune.

In the present work, we perform N-body simulations in order to see the evolution of less massive circumplanetary particle disks, and show that another satellite is secondly formed from a residual disk after the formation of the first satellite.

Method: We adopt the method of global N-body simulation. The orbits of particles are integrated with the 4^{th}-order Hermite method with shared timestep. All particles in the disk are initially identical size. Since the initial number of particles, N, in the simulation is large and distributed spatially, we have used the hierarchical oct-tree method to calculate gravitational forces with OpenMP parallelization. When particles are outside the Roche limit, particles start to form aggregates. However, when some of formed aggregates are scattered inside the Roche limit by mutual interaction, tidal effect of the central planet disrupts the aggregates. Therefore, rubble pile model that does not allow any accretion between particles would need to be used to investigate such satellite accretion process. However, rubble pile model accompanies much computation costs, and thus it is difficult to handle longer-term orbital evolution of formed aggregates. Here in order to solve collisions, we adopt what we call "clump-partial accretion model", which includes rubble pile model and allows artificial accretion under some limited conditions. As for rubble pile model, when we detect collisions, velocity changes are calculated based on the hard-sphere mode. We assume all particles are smooth spheres with normal coefficient of restitution ε_n=0.1. We update the biggest and the second biggest aggregate information (in terms of the masses) at regular intervals by using a clump-finding algorithm. Clump-finding starts from an arbitrarily chosen particle, and then iteratively detects any particles within a critical distance in bottom-up fashion. This procedure continues until no more particles are detected. Collisions between particles are basically solved based on the rubble pile model. However, particles that are the member of the detected biggest or second biggest clumps are treated differently. When those clumps satisfy some critical conditions, particles in the clumps are allowed to merge. We adopt the following critical conditions for merger: detected clump must be heavier than a critical mass, and its center of mass must be located outside a critical distance from the central planet. The critical values are chosen empirically. If both colliding particles are the member of the limited clumps that have met the accretion condition described above and if Jacobi constant $E_J < 0$ and their total physical radii < Hill radius, a collision is assumed to result in merging. Otherwise, they are solved based on the rubble pile model. When merging two bodies, the position and the velocity of the center of mass are conserved, and the total mass of the colliding bodies is combined into a new spherical body.

Initially, particles are randomly distributed from $R_{in}=0.4a_R$ to $R_{out}=1.0a_R$ with surface density $\Sigma(r)$ being proportional to r^{-3}. We performed several runs with initial disk mass $M_{D,init}$ of the order of $10^{-2}M_c$.

Results: In the case of relatively massive disk, the satellite first formed at the disk edge is relatively massive. Thus, a large amount of disk mass falls into the central planet while the formed satellite is repelled outward only a little by the disk. The final outcome is a single-satellite system and the mass of the primary satellite M_s is proportional to the initial disk mass $M_{D,init}$ [4,5]. However, in the case of less massive disk, our simulations showed that the dependence of the mass of formed primary satellite on $M_{D,init}$ is stronger, in agreement with the finding by [7], who also examined satellite accretion from less massive particle disks. In this case, a less massive satellite is formed and the satellite migrates outward by large distance through the interaction between the disk before the disk mass decreases considerably. When the satellite migrates outward enough and successively the disk edge moves outside the Roche limit, the second satellite is formed. Therefore, the final outcome is a multiple-satellite system. We have also found that in the above multiple-satellite system, the first and second satellites are in the 2:1 mean-motion resonance, which is also in agreement with [7]. This is because the first satellite wipes disk material up to the 2:1 resonance, and then the second satellite is formed from the materials piled up there.

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