EPSC Abstracts
Vol. 13, EPSC-DPS2019-1383-2, 2019
EPSC-DPS Joint Meeting 2019

EPSC
EPSC-DPS Joint Meeting 2019
15–20 September 2019 | Geneva, Switzerland

Formation and Orbital Evolution of the Uranian Satellites based on Giant Impact Scenario

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Abstract

We modeled a wide debris disk of solids with several conditions, performed N-body simulations to investigate the in-situ satellite formation from such disks, and constrained on the parameters of debris disks on the basis of a giant impact scenario. We found that the outer massive satellites can form around the current orbits from a wide debris disk with a few times the total satellite mass, whereas one or two extra large satellites generally form in the inner region of the disks. We then analytically calculated the orbital evolution of the satellites after their formation and found that such extra satellites would migrate inward due to the tidal torque from the planet and finally be disrupted by the planetary tides or fall onto the planet over several hundred million years. It can be possible that the Uranian rings form from the disrupted satellites and the inner regular satellites form by use of that ring materials. On the other hand, the outer satellites would almost not migrate but stay in their orbits because the tidal torque significantly decreases with the distance from the planet.

1. Introduction

Although the origin of Uranus's large axial tilt has not been known with certainly, one of the leading explanations for it is that an Earth-sized protplanet collided with proto-Uranus and then the rotation axis of Uranus was tilted [1]. The hydrodynamic simulations of such a collision, so-called a giant impact, have been carried out using the smoothed particle hydrodynamics (SPH) method, in which the fluid elements are represented by particles. The SPH simulations suggest that a giant impact could tilt the rotational axis of Uranus [2]. Until recently it had not been well investigated numerically how the Uranian satellites formed. However, recent SPH simulations with high resolution suggest that a circum-planetary disk including sufficient rock and ice materials would be produced throughout the current Uranian satellites orbits by the impact [3]. From such a wide disk, the current regular satellites can form in the current sites, and so that the giant impact scenario would explain both the large axial tilt and the formation of the regular satellites of Uranus simultaneously. Here in this study, we adopt the giant impact scenario and numerically investigate how the current Uranian satellites actually form from a wide disk.

2. Method

We performed N-body simulations to investigate that what kind of disks is suitable for the current satellite formation based on the giant impact scenario. In these calculations a particle represents a small rock-ice solid body to eventually form a satellite and gravitational interactions, collisions and mergers between particles are taken into account [4][5] . We modeled a wide debris disk of rock/ice solids with several conditions, assuming its surface density distribution is power-law with the semi-major axis, a, with represented as $\Sigma(a) \propto a^{-q}$ [5]. The power-index q is varied as a parameter on the basis of the results of SPH simulations [3]. The disk mass is also varied as a parameter and is several times the total satellite mass $M_{\rm tot}$, which equals to $\sim 10^{-4} M_{\rm Uranus}$. The inner edge of the initial disk is set to be Uranian radius ($R_{\rm Uranus} = 0.42 a_{\rm R}$), and the outer edge is $10 a_{\rm R}$, where $a_{\rm R}$ is the Roche limit of Uranus. Table 1 shows the model sets of the initial disks with the masses and the power-indices of the surface density distribution.

3. Results

Figure 1 shows the results of our simulations for the six disk models. The mass fallen onto Uranus is roughly a third of the initial mass in each case and the

Table 1: The model set of initial conditions.

Model	$M_{\rm disk}[M_{\rm tot}]$	q
Disk1	3	1.50
Disk2	4	2.15
Disk3	10	2.15
Disk4	4	1.95
Disk5	3	1.95
Disk6	3	3.00

total mass of the grown-up particles is larger than two-thirds of that. For the case of large q values, inner grown-up particles are too large while outer ones are too small, so a distribution of grown-up particles becomes totally different from the current satellite system. It can be speculated that the upper limit of q of an initial disk is roughly 2. If the initial disk mass is around $3.0M_{\rm tot}$, the sum of the particle masses in the outer region can become comparable to $M_{\rm tot}$ but mass excess in the inner region($R_{\rm Uranus} < a < 2a_{\rm R}$) occurs generally. We then analytically calculated orbital evolutions of the grown-up particles in the simulations due to the tidal torque by Uranus [6][7]. We found that extra grown-up particles inside the corotation radius($1.34a_{\rm R}$) would migrate inward and finally be disrupted by the planetary tides or fall onto the planet over several hundred million years, while those outside around the corotation radius would migrate outward and merge with outer grown-up particles. The outer particles would almost not tidally migrate but stay in their orbits during 4.5 billion years because the tidal torque significantly decreases with the distance from the planet. Considering the condition that the sum of masses remaining in their orbits is less than $M_{\rm tot}$, we speculate that $3.0M_{\rm tot}$ would be the upper limit of an initial disk mass. Thus, the extra large particles in the inner region would be cleared away and the outer grown-up particles with comparable masses and orbital radii would remain after the tidal orbital evolutions.

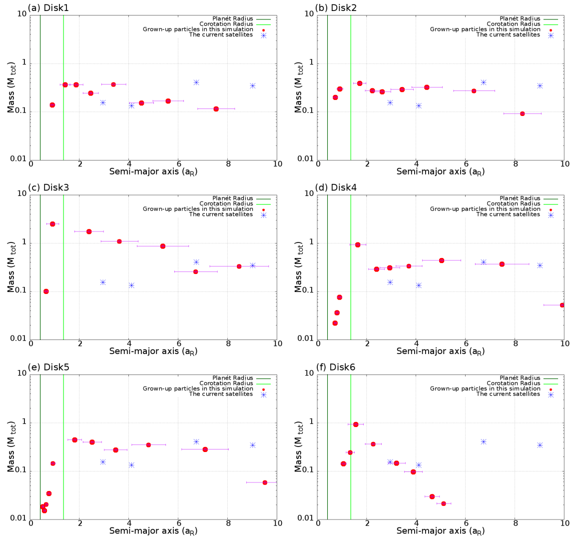

Figure 1: The satellite mass distributions for the six disk models when the disk particles totally accrete to grown particles. Red dots represent grown-up particle, dark-magenta bars indicate particle's Hill radii in these simulations, and blue stars represent the outer four satellites in the current. The dark green line and the green line indicate the planetary radius and the corotation radius, respectively.

Acknowledgements

This work was supported by JSPS KAKENHI grant number 19K03950. Some of numerical computations in this work was carried out at the Yukawa Institute Computer Facility.

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