EPSC Abstracts
Vol. 13, EPSC-DPS2019-393-2, 2019
EPSC-DPS Joint Meeting 2019

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

Early formation of satellites around 1000 km-sized trans-Neptunian objects via giant impacts

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Abstract

Six known trans-Neptunian objects have diameters larger than 1000 km, and all of them form satellite systems. The secondary-to-primary mass ratios and spin/orbital periods among these systems have a large variety and the origin of the satellites was unclear. Here we systematically performed hydrodynamic simulations to investigate satellite formation via giant impacts. We found that the simulated secondary-to-primary mass ratio overlaps with observed mass ratios and these satellites are directly formed as intact fragments of colliding bodies. We also revealed that the satellite systems' current distribution of spin and orbital periods and eccentricities can be explained when their spins and orbits tidally evolve, initially as fluid-like bodies and finally as rigid bodies. These results suggest that all satellites around 1000 km-sized trans-Neptunian objects might be formed via giant impacts in the early stage of solar system formation.

1. Giant impact simulations

We consider two scenarios for satellite formation via giant impacts: (1) accretion from an impact-generated debris disk, forming what we call hereafter "disk-origin moons", and (2) direct formation from the large intact fragments(s) of the impactor, which we call hereafter "intact moons". We used standard smooth particle hydrodynamics methods [1] to simulate the giant impacts and we performed 434 runs for 1000 km-sized planetary bodies, of which 141 resulting in the intact moon formation.

1.1 Intact moons

For giant impacts between two differentiated bodies with impactor-to-target mass ratio is 1:2, a large intact moon with secondary-to-primary mass ratio (γ) is ~ 0.1 formed via a grazing impact with the impact angle of 75° and the impact velocity is < 1.1 v_{esc} (v_{esc} is the two-body escape velocity), and smaller intact moons with $0.001 < \gamma < 0.1$ formed in wide parameter space in the impact angle and impact velocity. The observed γ ranges of the satellite systems is $\gamma \sim 0.1$ for Pluto-Charon system [4] and $0.001 < \gamma < 0.1$ for other systems [e.g., 3], then our simulated result is consistent with the observations. Similarly, for the case of giant impacts with two undifferentiated bodies, large intact moons formed during grazing impacts and smaller intact moons formed in wide parameter space.

In order to occur with reasonable frequency, giant impacts between 1000 km-sized trans-Neptunian objects (TNOs) must be gravitationally focused in the giant impact era. In this case, the typical impact velocity is ~ 1.0 v_{esc} and this is consistent with the formation of both large and small moons via giant impacts as intact moons.

1.2 Disk-origin moons

We also analyzed the disk mass around the primary at 10^6 seconds after giant impact and estimates the mass of the disk-origin moons. We found that the estimated mass of the disk-origin moon is always smaller than the typical mass of the observed satellites, however.

2. Tidal evolution calculations

The periapsis distance is typically ~ 3−4 R_p (R_p is the planetary radius of the primary) just after giant impacts. The eccentricity is distributed across all range from zero to one before the tidal evolution. We then performed semi-analytic tidal evolution calculations. Tidal evolution is found to be strongly dependent on the material states (e.g., rigidity), and we revealed that the intact moons ended up with circular orbits when they initially had small rigidity and behaved as fluid-like bodies, while most of the intact moons turned into eccentric satellites when they behave as rigid bodies since their formation.

We also found that the observed spin/orbital periods of the satellite systems could be explained when assuming planetary bodies would behave as fluid-like bodies for 10^4−10^6 years after giant impacts. In contrast, most of the satellite systems would reach a dual-synchronous state (i.e., the spin periods of satellite and the primary coincide with the orbital period) when the duration of fluid-like behavior was 4.5×10^9 years.

3. Discussion

From these results, we can give a constraint on the formation of large TNOs. The effect of impact heating might be limited for the case of 1000 km-sized bodies. The heat generation from tidal heating is also negligible when satellites were initially in solid-state. Therefore, 1000 km-sized TNOs were fully or partially molten before giant impacts. This implies that large TNOs which can store the radiogenic heat inside the bodies might be formed within the disk life time. In addition, small impact velocities inferred from giant impact simulations suggest that giant impacts between 1000 km-sized TNOs occurred before the outward migration of the outer planets including Neptune [2].

Acknowledgements

This work is supported by the Astrobiology Center Program of National Institutes of Natural Sciences (JY290107). S.A. is supported by the Grant-in-Aid for JSPS Research Fellow (JP17J06861). R.H. acknowledges the financial support of JSPS Grant-in-Aid for JSPS Fellows (JP17J01269) and for Early-Career Scientists (JP18K13600). H.G. is supported by MEXT KAKENHI Grant (JP17H06457).

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