巨大天体衝突による天王星衛星形成

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佐々木貴教

CPSセミナー@Zoom 2022/10/07
本日の内容

起：太陽の周りを横倒しで回る天王星系

承：巨大天体衝突で天王星の衛星は作れるか？

転：天王星周囲に形成された円盤は進化する！

結：新しい天王星衛星形成シナリオの完成（？）
   Kihara, Sasaki & Ida, *to be submitted*
太陽系の惑星の自転
1.2 Scenarios of satellite formation

How these satellites are formed? Several scenarios have been proposed so far to explain the origins of satellites including the Uranian satellites.

- Gas-starved disk model (e.g., Canup and Ward, 2002, 2006): Satellite growth and loss are repeated in the circum-planetary disk produced by a slow inflow of gas and ice-rock solids from solar orbit during the end stages of the formation of the Solar System. When the mass supplies terminate, the last generation of this cycle are left in orbits.

- Viscous spreading disk model (e.g., Crida and Charnoz, 2012): A disk of solid material around a planet, like Saturnian rings, spread due to the disk’s viscosity beyond the Roche limit (inside which planetary tides prevent aggregation). Satellites are formed outside the Roche limit, migrate outward due to the tidal torque from the planet and the disk.

- Giant impact scenario (e.g., Slattery et al., 1991): A planetary body collide with a planet, materials from the two bodies are ejected around. The ejected materials form a disk around the planet and one or more satellites are formed from the disk.

The representative studies of these scenarios are presented below in more detail.
天王星衛星星系の形成メカニズム（1）
As material migrates beyond the Roche radius, in excellent agreement with Saturn’s satellite systems. This suggests that Uranus and Neptune used to have massive rings that disappeared to give birth to most of their regular satellites. When the spreading is fast, only one large satellite forms, as was the case for Pluto and Earth. This conceptually bridges the gap between terrestrial and giant planet systems. Therefore, we propose that, in the Solar System, the period when the satellite systems spread beyond the Roche radius (inside the orbital radius) but a planet experiences a positive gravitational torque, is the period of migration of a satellite in an external orbit. This period is roughly the time during which the satellite is in a steady state, before the gas dissipates. These considerations suggest that an alternative model is needed, to explain at least the origin of the satellite of mass $q = M_{\text{satellite}} / M_{\text{planet}}$.

When a planetary tidal disk is fed by inflow of solids. Two competing models exist for the pyramidal regime. One is inflow of solids. Two competing models exist for the pyramidal regime. One model is based on self-gravity and mutual collisions, and the other is based on viscosity and planetary tides. The latter is consistent with the mean density of satellites, or with the orbit of the closest satellite from Pandora to Titan. Uranus, Neptune, and not the equatorial plane of the tilted planet. Thus, the normalized disk lifetime can be determined by the vertical dashed line. Jupiter: Metis, Adrastea, Icarus, Hestia, Himala, and Himalia. The four systems do not extend all the way down to the planetary radius (vertical line), but a planet experiences a positive gravitational torque. This gravitational torque is due to the mutual collisions of the small bodies, which are repelled by the tidal forces. The small bodies then aggregate to form a large satellite. This process is known as the pyramidal regime. The satellite of mass $q = M_{\text{satellite}} / M_{\text{planet}}$.

$\Delta = (r - r_0) / r_0$, where $r_0$ is the orbital radius. Thus, the normalized disk lifetime can be determined by the vertical dashed line. The four systems do not extend all the way down to the planetary radius (vertical line), but a planet experiences a positive gravitational torque. This gravitational torque is due to the mutual collisions of the small bodies, which are repelled by the tidal forces. The small bodies then aggregate to form a large satellite. This process is known as the pyramidal regime. The satellite of mass $q = M_{\text{satellite}} / M_{\text{planet}}$.

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Giant impact simulation (SPH; N=8,000)

Co-accretion + giant impact concept
Morbidelli et al. (2012)

Slattery et al. (1992)
Salmon & Canup (2022)
The white dashed circle traces out the current Roche radius of Uranus for reference. The snapshot times are $t = \text{unbound}$. Kegerreis et al. orbit, are $S92$, 2018 July 1. The angular momenta of the systems ranged from 1 to $5.8 \times 10^{-3}$. For the more head-on collision, the impactor core and planet varied from roughly 1 to 7 Earth days. The simulations significantly affect the results. The green points show the impact simulations typically contained \( \text{N = 100,000-1,000,000} \) particles. Using a Courant factor of 5.5, we are able to satisfy this requirement, provided that the impactor starts to only graze and eventually misses the target, making it unable to transfer enough of its huge angular momentum of at least $2 \times 10^{36} \, \text{kg m}^2 \, \text{s}^{-1}$. At first, raising the material available for moon formation and the distribution of material distributions is delivered more efficiently to the core of the planet varied from roughly 1 to 7 Earth days. The simulations found that this choice does not significantly change over timescales of 10,000 years. Depending on the angular momentum and impactor mass, the radial density production was split into categories into which the particles are placed: $10^{-2}$, $10^{-1}$, $10^0$, $10^1$, $10^2$, $10^3$, $10^4$. Considering the suite of simulations in full, Figures 4 and 5 show the angular momentum increases the material density. The density production was split into categories into which the particles are placed: $10^{-2}$, $10^{-1}$, $10^0$, $10^1$, $10^2$, $10^3$, $10^4$.
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巨大天体衝突による天王星衛星形成シナリオ

1. 異形惑星の衝突
2. 旋盤面形成
3. 卫星形成

衝突異形惑星モデルによる巨大衝突エネルギーのモデル化は、スムーズな粒子流動法（SPH）を用いることで行われる。スレッジャーら（1992）は、衝突モデルの質量（1〜3地球質量）が、曲げ慣性モーメントの周期と天王星の大きな傾斜を説明することができるとの結論を得た。彼らは、衛星形成の要素として、衛星の形成時における異形惑星材料の一部を衛星として取り込むことを提案している。

衝突によって形成されるリングは、高エネルギーと高温であるが、冷却過程を経ることになる。しかし、SPH法では他の流動変動を扱うのは難しい。ワード（2017）は、半球盤形成のパラメータを解析した。彼は、惑星の半球盤の半徑における流砂状変動を考慮した。彼は、衛星形成の要素として、衛星の形成時における異形惑星材料の一部を衛星として取り込むことを提案している。

Ishizawa et al. (2019)
Method (N-body simulation)

- Equation of motion:
  \[
  \frac{d^2 r_i}{dt^2} = -\sum_{j\neq i} G m_j \frac{r_i - r_j}{|r_i - r_j|^3}
  \]

- **Number of disk particles**: \(N_{\text{disk}} = 10,000\)

- **Collisions** are moderately inelastic, and **mergers** occur if the Jacobi energy after the collision is negative (e.g., Kokubo et al., 2000)

- Using 4th Hermite scheme and Leap Frog method for the numerical time integration

- Using FDPS for speeding up calculations
  (Framework for Developing Particle Simulator; Iwasawa et al., 2016)

Disk models with negative gradient

- Surface density of a circumplanetary disk generated by a GI is assumed to have a power-low distribution

  - **Disk size** \(a\) → \(R_U < a < 25R_U\)
  
  - **Disk mass** \(M_{\text{disk}}\) → Several times \(M_{\text{tot}}\) (the total satellite mass)

  - **Surface density** \(\Sigma(a) \propto a^{-q}\) → The power-index \(-q\) is varied as a parameter

  \[
  \Sigma \propto a^{-q}
  \]

<table>
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<th>(q)</th>
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<th>Disk3</th>
<th>Disk4</th>
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<td>(3M_{\text{tot}})</td>
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<td>1.95</td>
<td>3.0</td>
<td>2.15</td>
<td></td>
</tr>
</tbody>
</table>

These disk models have **negative gradients** directly inferred from the results of the SPH simulations (Kegerreis et al., 2018)

(C) Yuya Ishizawa
Results of N-body simulations for a disk model with negative gradient.

Extra massive satellites: $R_U < a < 7R_U$

Too large satellites: $7R_U < a < 13R_U$

Too small satellites: $13R_U < a$

After several thousand years, some particles have comparable masses to the current satellites, but the mass-orbital distribution is different from the current system.

Disk 1:
- $M_{\text{disk}} = 4.0M_{\text{tot}}$
- $q = 2.15$

Ishizawa et al. (2019)
Corotation radius: the orbital radius where a satellite has an angular velocity equal to a spin angular velocity of a planet.

$$\Omega = \omega(a) \rightarrow a = r_c$$

Inside $\Omega < \omega$, receiving negative torque $\Rightarrow$ Orbital decay

Outside $\Omega > \omega$, receiving positive torque $\Rightarrow$ Orbital growth

The corotation radius of Uranus $r_c \sim 3.3R_U$
A satellite’s semi-major axis evolves according to

\[
\frac{da_s}{dt} = \text{sgn}(a_s - r_c) \frac{3k_2D M_s G^{1/2} R_p^5}{Q_p M_p^{1/2} a_s^{11/2}}\]

(Charnoz et al. 2011)

\[k_2 = 0.104\] 

(Gavrilov and Zharkov 1977)

\[Q_p = 11,000\] 

(Tittemore and Wisdom 1989)

The corotation radius of Uranus \(r_c \sim 3.3R_U\)

- Inner satellites fall into Uranus or move outward
- Satellites in the middle merge each other
- Outer satellites (>10RU) remain in the almost same orbits

Ishizawa et al. (2019)
1. Satellites with similar mass are formed.

2. Inner satellites move inward and are destroyed.

3. Destroyed satellites form rings around Uranus.

4. Small satellites are secondarily formed from rings

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**Figures**

- **A**: Continuous regime (1 moon)
- **B**: Discrete regime (2 moons)
- **C**: Pyramidal regime (many moons)

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**References**

1. Gas-starved disk model (e.g., Canup and Ward, 2002, 2006): Satellite growth and loss are repeated in the circum-planetary disk produced by a slow inflow of gas and ice-rock solids from solar orbit during the end stages of the formation of the Solar System. When the mass supplies terminate, the last generation of this cycle are left in orbits.

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**Crida & Charnoz (2012)**

(C) Yuya Ishizawa
We performed N-body simulations and analytical calculations to investigate the possibility of the in-situ satellite formation from a debris disk around Uranus produced by GI.

Summary of Chapter 2

When the disk surface density has a negative power law gradient,

- satellites with too large masses would form around the orbit of Ariel and Umbriel
- the outermost satellites would not reach to the mass and the orbital radius of Oberon

It would be difficult to reproduce the distribution of the current satellite system from a debris disk with a negative gradient. The five major satellites would form in the current site. The small inner moons may form from rings of disrupted satellites as Crida & Charnoz (2012) Ishizawa et al. (2019)
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Protoplanets collide each other

Disk evolution

Satellite formation

(C) Yuya Ishizawa
Evolution model by Ida et al. 2020

1. Uranus Gas disk
An impact generates a gas disk of H/He and vaporized H$_2$O and rock

2. Uranus Gas disk
Viscous diffusion and radiative cooling of the gas disk

3. Uranus Gas disk Ice
Ice condensates when $T_{\text{disk}}$ falls bellow the freezing point of H$_2$O

4. Uranus Ice
A disk of ice has more mass on the outer side

(C) Yuya Ishizawa
円盤進化モデル

- **Viscosity** \( \nu \) (Shakura & Sunyaev 1973)
  \( \alpha \) is a constant parameter to represent the turbulence strength
  \( \nu \sim \alpha c_s^2 \Omega^{-1} \)

- **Local disk temperature** \( T \)
  Equilibrium between viscous heating and radiative cooling
  \( T \sim \left( \frac{9 GM_U \Sigma_g \nu}{8 \sigma r^3} \right)^{1/4} \)

- **Surface density of gas (H/He/H\(_2\)O) \( \Sigma_g \)**
  Surface density evolves according to the viscous diffusion equation
  \[
  \frac{\partial \Sigma_g}{\partial t} - \frac{1}{r} \frac{\partial}{\partial r} \left[ 3r^{1/2} \frac{\partial}{\partial r} (\Sigma_g \nu r^{1/2}) \right] = 0
  \]

Iida et al. (2020)
円盤内での氷の凝縮

Ice condensation occurs at T ~ 240K

Time = 10, 10^2, 10^3, 10^4

Ida et al. (2020)
最終的に形成される氷円盤の解析解

\[ \Sigma_{\text{ice}} \simeq \gamma \Sigma_{\text{g}} \simeq 1.2 \times 10^2 \beta^{-1} \gamma_{03} \left( \frac{r}{r_U} \right)^{3/2} \ \text{kg m}^{-2} \]

\[ r_{\text{max}} \simeq 20 \left[ \beta \left( \frac{r_{\text{d,imp}}}{2r_U} \right)^{5/4} \left( \frac{M_{\text{d,imp}}}{10^{-2} M_U} \right) \right]^{1/4} r_U \]

\[ M_{\text{ice}} \simeq \int_{r_U}^{r_{\text{max}}} 2\pi r \Sigma_{\text{ice}} \, dr \simeq 0.58 \times 10^{-4} \beta^{1/8} \gamma_{03} \left( \frac{r_{\text{d,imp}}}{2r_U} \right)^{-5/4} \left( \frac{M_{\text{d,imp}}}{10^{-2} M_U} \right)^{7/8} M_U \]

Ida et al. (2020)
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天王星衛星形成のN体シミュレーション（改）

表面密度

\[ \Sigma \propto a^{-q} \]

\[ M_{\text{disk}} \]

半径 25R_U

表面密度

\[ \Sigma_{\text{ice}} \propto a^{1.5} \]

\[ M_{\text{disk}} \]

半径 20R_U

\[ M(M_U) \]

\[ r(r_U) \]

Ida et al. (2020)
Disk diffusion timescale: \( t_{\text{diff}} \simeq t \simeq 9.2 \times 10^5 \left[ \beta \left( \frac{\langle r_{\text{d,imp}} \rangle}{2r_U} \right)^{-5/4} \left( \frac{M_{\text{d,imp}}}{10^{-2}M_U} \right) \right]^{22/21} \left( \frac{\alpha}{10^{-3}} \right)^{-1} \Omega^{-1} \)

Drift timescale of icy particles due to gas drag: \( t_{\text{drift}} \simeq \frac{r}{v_r} \simeq \frac{r}{2\eta} \frac{1 + St^2}{v_K} \simeq 0.5 \left( \frac{c_s}{v_K} \right)^{-2} \frac{1 + St^2}{St} \Omega^{-1} \)

Growth timescale of icy particles: \( t_{\text{grow}} \simeq 1 \left( \frac{St + \alpha}{10^{-4}} \right)^{-1/2} \left( \frac{\gamma}{0.3} \right)^{-1} \left( \frac{\alpha}{10^{-3}} \right) \left( \frac{T_{\text{ice}}}{240 \, \text{K}} \right)^{-11/4} \left( \frac{r}{r_U} \right)^{-3/4} \Omega^{-1} \)

Type-I migration timescale of a satellite: \( t_{\text{mig}} \simeq \frac{1}{2.7 + 1.1 \times (3/4)} \left( \frac{M_U}{m} \right) \left( \frac{M_U}{\Sigma gr^2} \right) \left( \frac{c_s}{v_K} \right)^2 \Omega^{-1} \)

\( c_s < v_K, \ \alpha \ll 1, \ St \simeq 1 \quad \rightarrow \quad t_{\text{grow}} \ll t_{\text{drift}} \ll t_{\text{diff}} \ll t_{\text{mig}} \)

Ida et al. (2020)
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GI scenario for the uranian satellite formation

Protoplanets collide each other
SPH method

Satellite formation
N-body

The current satellites could not form from a debris disk with a negative gradient
The evolution of an impact-generated disk is not considered

In Chapter 1, here we performed an N-body simulation for the condensed ice disk suggested by the evolution of the impact-generated disk of a mixture of water vapor and H/He gas until the disk cools down enough for ice condensation

✦ A disk generated by a giant impact is mostly vaporized
✦ It may undergo viscous diffusion until the re-condensation of materials

Ida et al. (2020)
Ishizawa et al. (2019)
Ida et al. (2020)
Woo et al. (2022)

Slattery et al. (1992)
Kegerreis et al. (2018)
Kurosaki & Inutsuka (2019)
Reinhardt et al. (2020)
Woo et al. (2022)
大量のN体計算による統計的検証

Table 1. Model sets of initial condition

<table>
<thead>
<tr>
<th>Run</th>
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Kihara et al., to be submitted
典型的な計算結果の1例

図1. 射6の結果（$10^7$秒後）。
横軸は衛星の半径主軸、縦軸は質量を示します。
青い円はシミュレーションの結果。
赤い円はミランダ、アリエル、アンブリエル、テトリア、オーバロンの、 Uranusの5つの最大の衛星を示しています。
各円のサイズは衛星の質量に対応しています。

(a) 各衛星の傾き
(b) 各衛星の軌道傾角

図2. 射6の結果の各衛星の傾き。
青い円はシミュレーションの結果。
赤い円はUranusの5つの最大の衛星を示しています。
ミランダの傾角（$4.2^\circ$）はここには表示されていません。

Kihara et al., to be submitted
Figure 4. The red circles are Ariel, Umbriel, Titania, and Oberon. The blue circles are the average values of produced satellites, and error bars are 1. Numbers of extracted runs are 6, 8, 9, 13, 15, 19, and 23.

4.2. Satellites outside the Oberon

Figure 5 shows the current Uranian satellites system known from observations. No large prograde satellites have been discovered outside of Oberon (only one prograde satellite is discovered outside of Oberon, but it is very small), while our simulations always produced several satellites there. Since very small satellites have been discovered outside of 100 r_U, if satellites actually exist at 30 100 r_U, they must have been discovered by observations. So we need the mechanisms to resolve the discrepancy between our simulation results and the current satellites system.

First, we considered the possibility that these outer satellites would collide with Oberon. If the outer satellites have been scattered by the inner large satellites, their eccentricity would be large and they would collide with the Oberon near their perigee. To examine this, we calculated the eccentricities and perigee distances of the outer satellites, and compared Oberon's semi-major axis with the perigee distances of each satellite. Then, we found almost all outer satellites have larger perigee distances than the Oberon's orbit. Therefore, these outer satellites would remain without collisions.

The other possibility is the protoplanets' encounters. Protoplanets may pass through the vicinity of Uranus after their satellites had been formed. Ida et al. (2000) showed that the high eccentricity and inclination observed in the outer part of the Edgeworth-Kuiper belt (42 au) can be explained by early stellar encounters to the solary system. A similar event on Uranus, though on a very different scale, would increase the eccentricity of the outer satellites and could result in a collision with Oberon. In order to confirm the scenario, we need to estimate the probability of such encounters and investigate the gravitational interactions between the protoplanet and the satellites.

5. CONCLUSION

We performed N-body simulations based on the debris disk model of Ida et al. (2020) and investigated whether we could reproduce the current Uranian satellite system. We found that, in most cases, the smaller satellites were formed in the inner area and the larger ones in the outer area.

- Averagely four large satellites are formed and the smaller satellites locate in the inner area and the larger ones in the outer area.
- Only one satellite is formed around Ariel and Umbriel's orbits.
- A large satellite is robustly formed around 13 Ru where between Umbriel and Titania's location.
- Several satellites are formed outside of Oberon where no satellites have been discovered.
The orbit-crossing time \( \text{Zhou et al. (2007)} \)

\[
\log \left( \frac{T_c}{\text{1 yr}} \right) = A + B \log \left( \frac{k_0}{2.3} \right)
\]

\[
A = -2 + \frac{e}{h} - 0.27 \log \frac{m}{M_U}
\]

\[
B = 18.7 + 1.1 \log \frac{m}{M_U} - \left( 16.8 + 1.2 \log \frac{m}{M_U} \right) \frac{e}{h}
\]

The produced satellites will be scattered with each other by gravitational interactions via orbital crossing on a timescale about \(10^6\) years, then move into the current orbits.

1. \(k_0 = 12.0, \ T_c = 3.3 \times 10^7 \ [\text{yr}]\)
2. \(k_0 = 9.0, \ T_c = 1.7 \times 10^6 \ [\text{yr}]\)
3. \(k_0 = 8.7, \ T_c = 7.5 \times 10^5 \ [\text{yr}]\)
Produced via accretion

1. The outer satellites will collide with Oberon?
   —> No; they have larger perigee distances than the Oberon’s orbit.

2. Protoplanets’ encounters to the Uranian system?
   —> Possibly; we need to estimate the probability of such encounter events.

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本日の内容

起：太陽の周りを横倒しで回る天王星系

承：巨大天体衝突で天王星の衛星は作れるか？

転：天王星周囲に形成された円盤は進化する！

結：新しい天王星衛星形成シナリオの完成（？）
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