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The exchange of mass and angular momentum in giant impact on Uranus: The effect of the inflated atmosphere

Kenji Kurosaki and Shu-ichiro Inutsuka
Nagoya University, Japan (kurosaki.k@nagoya-u.jp)

Abstract

A giant impact event changes the planetary rotation rate. Uranus has large obliquity which is supposed to caused by a giant impact. We execute hydrodynamic simulations for the giant impact on Uranus-size target which is composed of a water core surrounded by a thick hydrogen atmosphere. We investigated the effect of the target's thermal states and find that the higher-entropy target gains more angular momentum than the low-entropy target during the giant impact since the higher-entropy target's radius is larger than lower-entropy one. Our results may derive the information about the impact events of planetesimals in the formation stage of the ice giant.

1. Introduction

An impactor of several earth mass may have transported angular momentum to proto-Uranus via collision and tilted the rotation axis of proto-Uranus. Previous studies calculated the giant impact based on the smoothed hydrodynamic simulation and they concluded that the minimum impactor mass is order of several Earth mass [3]. Such a large impact event may also have produced a circumplanetary disk around proto-Uranus, which might have been the origin of the small prograde satellites around Uranus [4]. In this paper, we study the impact event on proto-Uranus. The aim of this paper is to investigate the envelope erosion and the efficiency of angular momentum transport to proto-Uranus. Since there are no constraints on the age of Uranus at the time of the impact event, we consider two extreme cases: an impact onto a young (10^8 yr) ice giant, when it was in a high-temperature state, and an impact onto a mature ice giant (10^9 yr), when it was in a low-temperature state.

2. Method

We solve the following hydrodynamic equations by use of the Godunov-type smoothed particle hydrodynamical calculation, hereafter GSPH,

$$\begin{aligned} \frac{d\rho}{dt} &= -\rho\nabla\cdot\mathbf{v} && (1)\\ \frac{d\mathbf{v}}{dt} &= -\frac{1}{\rho}\nabla P + \nabla\int dx'^3\,\frac{G\rho(x')}{|\mathbf{x}-\mathbf{x}'|} && (2)\\ \frac{du}{dt} &= -\frac{P}{\rho}\nabla\cdot\mathbf{v} && (3)\\ P &= P(\rho,u) && (4)\end{aligned}$$

where ρ, P, $\mathbf{v}$ and u are density, pressure, velocity, and specific internal energy, respectively. t is the time, $\mathbf{x}$ is the position, and G is the gravitational constant. The detail of our numerical method is described in [6]. We set the impact velocity (hereafter $v_{\rm imp}$) is equal to the escape velocity (hereafter $v_{\rm esc}$);

$$v_{\rm imp} = v_{\rm esc} = \sqrt{\frac{G(M_{\rm target}+M_{\rm impactor})}{(R_{\rm target}+R_{\rm impactor})}} \qquad (5)$$

where $M_{\rm target}$ is the target's mass, $M_{\rm impactor}$ is the impactor's mass. $R_{\rm target}$ is the target's radius, and $M_{\rm impactor}$ is the impactor's radius, respectively.

Properties of the target and the impactor are shown as Table 1. Here we assume two types of targets. The high-temperature target, hereafter HT, is assumed to have entropy $S = S$(1 bar, 270 K), while the low-temperature target, hereafter LT, is assumed to have entropy $S = S$(1 bar, 120 K). The thermal evolution stage among HT, LT, and present Uranus is shown in Fig. 1. In this study, we consider the targets whose ages are $\sim 1\times10^8$ years for HT and $\sim 1\times10^9$ years for LT. The detail of the numerical method of the interior structure is described in [5].

3. Results

Here we define the target as the particles that satisfy the condition:

$$\frac{1}{2}m_i v_i^2 - \sum_{i\neq j}\frac{Gm_i m_j}{|\mathbf{x}_i-\mathbf{x}_j|} < 0, \qquad (6)$$

Table 1: Properties of the target and the impactor.

Properties	HT Target	LT Target	Impactor
Mass [10^{27} g]	78.2	78.2	5.97
Radius [10^9 cm]	3.18	3.03	1.13
H_2 [%]	20	20	0
H_2O [%]	80	80	100

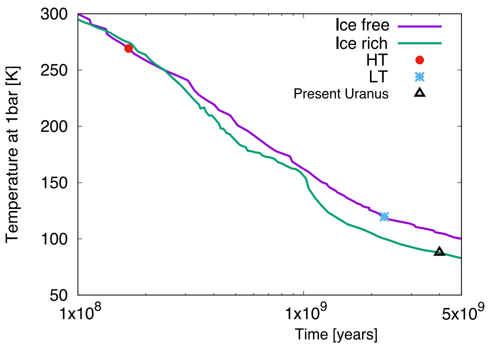

Figure 1: The thermal evolution stage for HT and LT. Lines colors means the difference of the ice mass fraction in the atmosphere (see also [5])

where m is the particle's mass and v is the particle's velocity, respectively. The subscripts i, j are the particle's number. Eq. 6 represents the particle which is bounded by the gravity.

Figure 2 shows the result of the target's angular momentum after the giant impact. We can find that the HT target gains more angular momentums than the LT target since the HT target has larger radius than the LT target.

4. Summary and Conclusions

We have performed numerical simulations of a giant impact on a young Uranus-like ice giant using the Godunov SPH simulation with realistic structures composed of ice and hydrogen-helium gas in the case of no initial rotation of the target. We find that if the target is in a high-entropy state, it obtains larger angular momentum and lose its envelope more efficiently than the low-entropy state, because the hydrogen envelope of the high-entropy target is significantly more extended. Our results also show that less mass remains gravitationally bound in the high-entropy target than in the low-entropy target. Our results may provide a step forward to understanding the origin of Uranus.

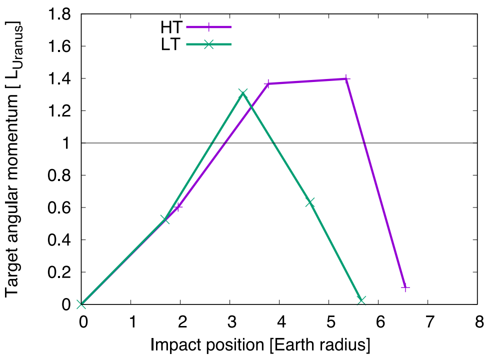

Figure 2: The angular momentum which target gains after the giant impact.

Acknowledgements

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