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Numerical simulations on the formation of Ultima-Thule

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Abstract

The first Kuiper-belt contact binary (486958) 2014 MU69 has been confirmed earlier this year by the New-Horizons spacecraft mission during the first fly-by. The two bodies, Ultima and Thule, being almost fully intact implies that the formation is likely due to a slow merging impact. We therefore investigate the outcome of such slow impacts using a SPH code to perform hydrodynamic simulations. We vary the impact velocity, the strength of the two bodies, as well as the impact angle to cover the most probable scenarios. Our goal is to get a reasonable parameter space for the formation of such a binary which does not deform, has the correct rotation speed of Ultima-Thule and to furthermore show that occasional high impact velocities result in disruptional collisions.

1. Introduction

The New-horizons spacecraft took high resolution images of the cold classical belt object (486958) 2014 MU69 (Ultima-Thule), which confirmed that the object is indeed a contact binary of two similar sized ellipsoids with radii 9.75 and 7.1 km [7]. The rotational period of Ultima-Thule is around 15 hours, which is consistent with classical belt objects but far from the critical breakup velocity, thus making rotational breakup formation implausible.

2. Impact model

We use a SPH code developed by [8] to perform hydrodynamical collision simulations. The *miluphCUDA* code is implemented via CUDA and runs on graphics processing units (GPU). The code has already been successfully applied to several studies involving impact processes [2, 6, 9].

The code can treat self-gravity, as well as gas, fluid, elastic, and plastic solid bodies with material strength, including a porosity model which can be applied for small- as well as large-body collisions.

The porosity is implemented using the so called $P{-}\alpha$ model [3].The dependence is expressed in terms of the porous material pressure P, such that:

$$P = \frac{1}{\alpha} P_s(\rho_s, E_s) = \frac{1}{\alpha} P_s(\alpha\rho, E), \qquad (1)$$

where P_s is the pressure, ρ_s the density and E_s the energy of the *solid* matrix material and $\alpha = \rho_s/\rho$ is the distention. For the solid matrix material we use the Tillotson equation of state (EOS), with the parameters for Pumice [5]. The matrix density is chosen to be 2 g cm^{-3} Assuming a bulk density for Ultima-Thule of 1 g cm^{-3} implies an initial porosity of 50%.

The simulations with different strengths are done using four different sets of crush curve parameters (the same approach was used by [4]).

We use a simple quadratic crush curve [3] in order to define $\alpha = \alpha(P)$:

$$\alpha = 1 + (\alpha_0 - 1)\frac{(P_s - P)^2}{(P_s - P_e)^2}, \qquad (2)$$

where $\alpha_0 = 2$ is the initial distention, P_e is the transition pressure between the elastic and plastic regime and P_s denotes pressure at which the material is fully compacted. The four sets of crush curve parameters are listed in Table 1. Our lowest-strength crush curve values correspond to the intermediate-strength values from [4] since we assume 67P/Churyumov-Gerasimenko to be more fluffy and porous. Our highest-strength values equal those of [5].

We use a simple von Mises plasticity model with a constant yield strength. Fracture and brittle failure are treated using the Grady–Kipp fragmentation prescription [1]. For additional details regarding the *miluphCUDA* implementation of the porosity and fracture model refer to [10] and [2].

In order to see if the contact binary can be reproduced with typical impact velocities equal to v_{esc} we

Table 1: Crush curve parameters.

Type	P_e	P_s	α_0
Lowest-strength	10^3	10^5	2
Low-strength	10^4	10^6	2
Intermediate-strength	10^5	10^7	2
High-strength	10^6	2.13×10^8	2

examine following aspects:
Shape: can Ultima and Thule merge softly, almost without deforming, for different crush curve parameters with $v_{imp} = v_{esc}$?
Rotation rate: which impact angles result in the present day rotation rate of Ultima-Thule?
Disruption: can it be explicitly shown that random, high velocity impacts (e.g. $v_{imp} = 10 \times v_{esc}$) do not reproduce the observed properties of Ultima-Thule?
We therefore perform a number of impact simulations with impact angles between 5-50^o, with 5^o increments, a fixed impact velocity v_{esc} and four sets of crush curve parameters from Table 1.

Figure 1 shows a merging impact with almost no deformation of the binary. For high impact velocities around $v_{imp} = v_{esc}$ we get disruptional collisions.

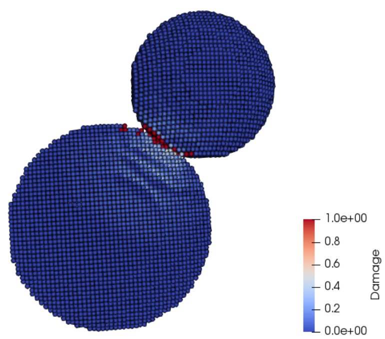

Figure 1: Merging impact with $v_{imp} = v_{esc}$. Colour plotted is the damage.

3. Summary and Conclusions

We use hydrodynamical simulations to show that Ultima-Thule can be formed for a plausible range of initial parameters of the collision. Since the impact velocity is relatively low, the shape is undeformed for most of the runs. The rotational period is compatible with the observations if the impact angle is ~ 40 deg, or if the closest approach distance is $q/R_{\rm tot} \sim 0.6 - 0.7$.

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