HAUMEA'S FORMATION AND EVOLUTION FROM A GRAZE-AND-MERGE IMPACT. J. L. Noviello[1], S. J. Desch[1], and M. Neveu[2] [1]School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287. [2]NASA/Goddard Space Flight Center, Greenbelt, MD 20771. Jessica.Noviello@asu.edu

Introduction: The Kuiper Belt Object (KBO) and dwarf planet Haumea is the fastest-rotating large body in the solar system, with rotational period P = 3.91531±0.00005 hours [1]. Its surface is almost pure water ice [2], as are the other members of its associated collisional family [3], including its two modern satellites. These clues point to a large impact event, likely > 3 Gyr ago [4], that created the collisional family, satellites, and modern-day Haumea. There are multiple models that explain parts of Haumea's evolutionary history [3,5,6], but no single one explains all the observations, in particular the low total mass and orbital parameters of the family members [7].

Haumea has a nonaxisymmetric, triaxial ellipsoid shape. Occultation observations estimated Haumea's axes at a =1161±30 km, b =852±4 km, and c =513±16 km and its density 1885 kg m^{-3} [8], but recent modeling [9] using the `kyushu` code has constrained Haumea's axes to be $a\approx1050$ km, $b\approx840$ km, and $c\approx547$ km, with density ≈2018 kg m^{-3}.,This modeling also constrains Haumea to have a core with density ≈2018 kg m-3, and an ice mantle ranging from 71 to 170 km in thickness, accounting for 17% of Haumea's total mass. Although still not as ice-rich as other KBOs [10], this indicates that the collision did not necessarily strip all of proto-Haumea's ice mantle.

Explaining the collisional family is a challenge. The total mass of the icy collisional family members is only 3% of Haumea's mass [11], . and their velocity dispersions are <140 m s^{-1}, much lower than the escape velocity of Haumea, ~1 km s^{-1} [7]. Neither isotropic ejection nor ejection from a plane are consistent with their orbital elements. We propose a new hypothesis for the origin of Haumea and its collisional family, involving geoy-driven changes in its spin rate, and we constrain some of the conditions that would allow this.

New Hypothesis: We favor the initial conditions of the graze-and-merge hypothesis [6], in which two equally-sized bodies collided before they fully differentiated. Their cores merged and some material was stripped off, similar to the scenario of [12] as described for Pluto and Charon. As proto-Haumea continued to differentiate, its core grew and its moment of inertia decreased, increasing its angular spin according to the basic formula $\omega = J / I$, where J and I are Haumea's angular momentum and moment of inertia, and $\omega = 2\pi / P$ is the angular velocity.

At the tips of the poles of Haumea's long (a) axis, the centrifugal acceleration is $\omega^2 a$. If Haumea was spinning more rapidly in the past, the effective gravity at the tips of its long axes may have been close to zero, allowing material to fission off of Haumea. We hypothesize Haumea lost 3% of its current mass this way, generating the observed collisional family [11]. Haumea today is not spinning fast enough to allow this, but it must have been spinning much faster in the past, and slowed down, due to two effects: 1) loss of angular momentum by ejection of the family members; and 2) changes in its moment of inertia.

Using the `kyushu` code, we calculate that if Haumea today has the physical parameters described in [9], then its moment of inertia is I = 1.216 x 10^{33} kg m^2, and the gravitational acceleration on the tip of its a axis is 0.35 m s^{-2}, countered by centrifugal acceleration 0.21 m s^{-2}, yielding effective gravity 0.14 m s^{-2}. If the spin rate in the past was 3.02 hr, the effective gravity could have been close to zero, allowing escape of material. Loss of 3% of Haumea's mass from the tip of the a axis would have carried off 8.8% of Haumea's present angular momentum, slowing the rotation rate to 3.29 hr. If hydration of the core increased the moment of inertia by 19% (equivalent to increasing MOI from 0.315 to 0.375), then this would yield a spin rate consistent with Haumea's present-day value.

The very short rotation period of 3.02 hr was probably made possible by formation of a core during differentiation of the post-impact Haumea. This would have decreased the moment of inertia by a factor of 1.27, equivalent to a decrease in MOI from 0.4 to 0.315. As long as the impact formed Haumea from a partially differentiated state (allowing an ice mantle) with period ~ 3.83 hr, full formation of the core could have led to an increase in spin rate that would have ejected material from the tips of the a axis.

Necessary conditions of this scenario are that the collision that formed Haumea must have occurred before the impactors differentiated, so that Haumea could spin up over time. Additionally, temperatures inside Haumea must not exceed the dehydration temperature ≈ 600 K, so that its core density today can be 2600 kg m^{-3}, characteristic of hydrated silicates.

Methods: We use the code *IcyDwarf* [13] to simulate the coupled physical-chemical-thermal evolution of Haumea and its impactors, including the effects of rock hydration and dehydration, hydrothermal circulation, and core cracking. We first constrain the time of impact, assuming two identical bodies each with 50% of Haumea's mass, radius 640 km and density (assuming zero porosity) 2000 kg cm^{-3}. We also varied porosity and the ratio between rock:liquid water in the core, to compare the effects these variables have on the output of a Haumea-like but spherical body (radius of 840 km, density = 2018 kg cm-3, from [9]). The simulations are run for a total time of 5 Gyr.

Results: In **Figure 1** we show the moment of inertia factor I/MR^2 of the impactors vs. time. Despite some earlier changes, the cores of the impactors do not form until 165 Myr after accretion. For our hypothesized scenario to work, the bodies cannot have substantially differentiated, which would have lowered their moment of inertia. This means that the collision that formed Haumea could not have happened after 160 Myr, consistent with previous results [6].

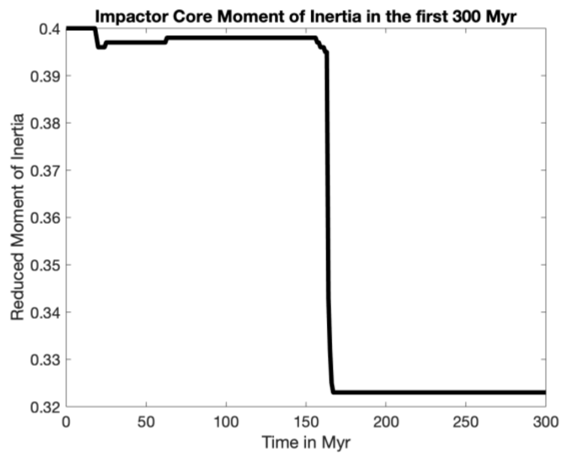

Figure 1: Moment of inertia factor I/MR^2 vs. time, for one of the Haumea impactors.

Haumea evolution: We are particularly interested in the evolution of the minerals within the core. To study this we must examine whether liquid water is able to reach the core via cracking and the effects of varying initial volume of ice in the core, another way for the core to become hydrated over time. As Haumea grows and differentiates, radiogenic and gravitational heating will occur. This will melt the ice accreted post-impact and may change the geochemistry of the system. We use IcyDwarf to study these changes in detail.

Our Haumea simulations initially varied porosity and the volume of ice in the core to compare the effects these variables have on the output. As total void porosity increased from 0 to 0.25, the maximum core size stayed constant at around 685 km out of the full 840 km radius for the modeled Haumea, and the core maximum temperature after 5 Gyr was upwards of 1921 K; this is consistent with what should be expected from conductivity of the material. As more ice is added to the core, the temperatures should remain fairly constant, as all the heat energy would go to melting the ice. As the ice:liquid water ratio increased from 0 to 0.4, the maximum core temperature at the final timestep (5 Gyr) remained constant at 271 K. The size of the core significantly increased as porosity increased, ranging from 700 km to 800 km out of the total 840 km radius of the modeled Haumea.

We also ran a simulation with no void porosity and 10% initial volume of ice in the core; the thermal plot for this run is shown in **Figure 2.** The orange in the graph represents 273 K, the melting point for ice. Between 2.3 and 3.9 Gyr, the core could have been hydrated by the ice that melted within it. Additionally, at no time does Haumea's interior exceed the dehydration temperature of 600 K. Our immediate next steps are to study the connection between the impactors' compositions and what it means for Haumea's initial conditions, and to explicitly demonstrate the geochemical changes that happen in the core and the effects of core cracking on core hydration.

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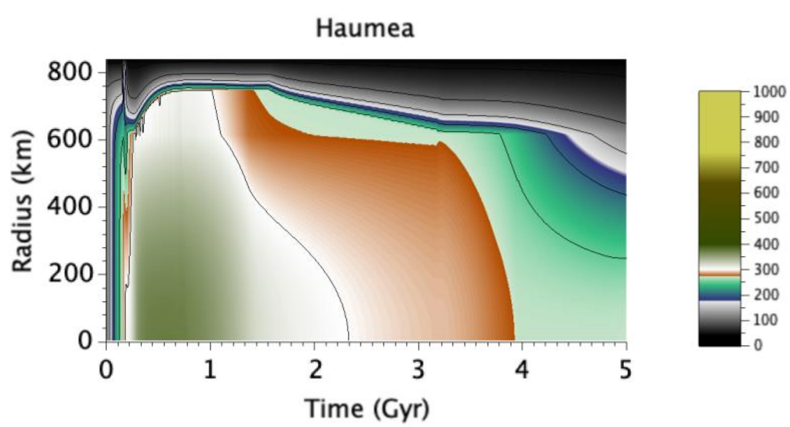

Figure 2: IcyDwarf code output the thermal evolution of Haumea. The orange area represents the volume where liquid water could have been. Note that the temperature anywhere never reaches above 600 K.