MODELING THE AXIS RATIOS OF A DIFFERENTIATED HAUMEA TO DETERMINE ITS INTERNAL STRUCTURE. E. Dunham[1], S. J. Desch[1], V. Perera[1] and S. R. Schwartz[1], [1]School of Earth and Space Exploration, Arizona State University, PO Box 871404, Tempe AZ, 85287 (etdunham@asu.edu).

Introduction: The Kuiper Belt Object Haumea is one of the most intriguing and puzzling objects in the outer Solar System. Haumea is remarkable because it likely experienced an early giant impact [1]. Clues leading to this hypothesis include its rapid rotation period of 3.9153 hours, multiple satellites, and dynamically-related family members [1]. Haumea's surface is spectrally nearly (> 98%) pure water ice [2,3], implying Haumea had differentiated into a rocky core and pure ice mantle, which the impact revealed by stripping the outermost layers. Different impact scenarios [1,4-6] could be distinguished if Haumea's internal structure were better understood.

Haumea's mass and inferred mean radius of about 718 km [7] imply a mean density of 2.58 g/cm^3. This high density suggests that Haumea is composed of a rocky core with an icy veneer. Haumea's light curve shows a $\Delta m \sim 0.3$ photometric variation over the rotation period [7-9]. Because of Haumea's surface uniformity [2], this light curve is due to varying area presented to the observer, and not albedo variations. Haumea's light curve and thermal emission have been successfully modeled assuming that Haumea is a homogeneous triaxial Jacobi ellipsoid (defined as $a > b > c$; $0.43 < c/a < b/a < 1$) of uniform density ~2.6 g/cm^3 [7, 8, 10]. These studies agree that Haumea's rotation axis is normal to the line of sight and that it reflects with a high-albedo icy-type scattering function [8,9]. The most recent study [9], which was able to resolve Haumea from its moons, predicts that Haumea dimensions are $960 \times 770 \times 495$ so that $b/a = 0.80$, and $c/a = 0.52$.

These two results are contradictory: Haumea cannot be uniform in density and have a rocky core surrounded by an icy crust. This could potentially invalidate the common use of a Jacobi ellipsoid solution [11] because the behavior of a differentiated body under fast rotation is uncertain.

We present preliminary results of our investigation into the effects of Haumea's high density and fast rotation on its peculiar elongated shape. Our numerical simulations test whether a differentiated Haumea-like body forms a Jacobi ellipsoid shape, or alternatively another triaxial ellipsoid shape.

Methods: We perform numerical simulations using the pkdgrav *N*-body code [12,13]. This code was used for previous Haumea studies [5,14] to test collisional scenarios, and the likelihood of Haumea forming by rotational fission. To study the shape of Haumea, we modeled the body as a rubble-pile: a gravitationally bound aggregate of 1,000 particles with no tensile strength [15,16]. Previous simulations [15] show that a thousand particles is sufficient to resolve general shape features in a rubble pile. An important difference between our simulations and those of [5] is that we use the soft-sphere discrete element method [SSDEM] described in [17], based on [18], whereas [5] used the hard-sphere discrete element method [HSDEM] from [12] as the collisional routine.

We created two different types of aggregates, both composed of 10,000 particles with a total mass equal to Haumea's mass (4.006×10^{21} kg; [19]). In the first case, all particles are 33.5 km in radius, have density

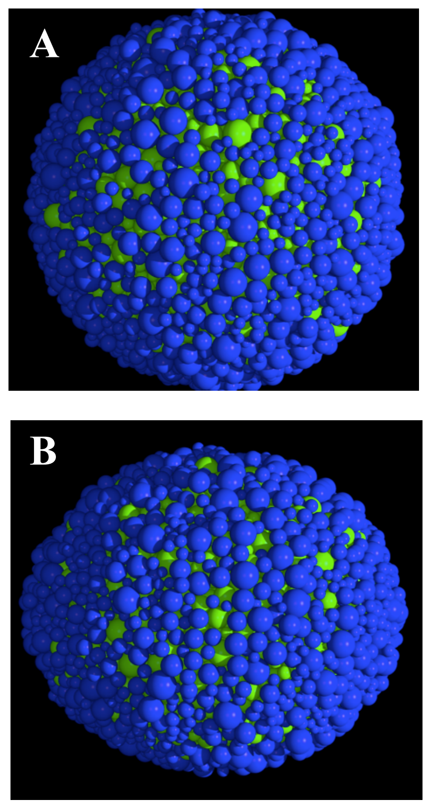

Figure 1 A simulated model (S2) of Haumea using 10,000 particles of different sizes (largest/smallest size ratio = 3; power law index = -3), composed of a rocky core (density ~ 3 g/cm^3; green particles) and an icy crust (density = 0.917 g/cm^3; blue particles). The aggregate evolved from image A (a sphere) to B (an oblate spheroid) as we spun it at Haumea's rotation period for ~30 hours (in simulated time).

2.584 g/cm^3, and are built inside a 3,000 km radius sphere. In the second case, the particles are different-sized: the smallest particles are 20 km in radius and the largest to smallest particle size ratio is 3 (power law index to -3 with a continuous distribution). They have the same density as case 1 and are built inside a 2,500 km radius sphere.

We allowed each aggregate to gravitationally settle and they have bulk densities and average radii comparable to Haumea. Then we altered the masses of the outer layer of particles for each aggregate to test different scenarios, and spun these aggregates to Haumea's rotation period. The goal was to determine if a homogeneous Haumea and a differentiated Haumea both form Jacobi ellipsoids. We determined the final shape of aggregates in three separate scenarios:

Scenario 1: S1 is a homogenous aggregate of density 2.6 g/cm^3. This case is a test to be certain we can reproduce a homogeneous Jacobi ellipsoid like [7-9]

Scenario 2: S2 is an aggregate with a ~30 km crust of ice I_h (hexagonal crystal form of ordinary ice; density 0.917 g/cm^3), the remaining portion of the body is density ~3 g/cm^3 for the total mass of the aggregate to equal Haumea's mass. This scenario was proposed by [11,20] who concluded that Haumea is nearly uniform in density with a thin, < 30 km, icy crust.

Scenario 3: S3 is an aggregate with a core of density 3.5 g/cm^3, the remaining portion of the body is composed of ice I_h. Here, the core has a radius ~700 km, so that the average density and mass of the aggregate are characteristic of Haumea. The core density we assumed here is that of Vesta [21].

These three aggregates were gravitationally settled, and spun to Haumea's rotation rate for 30–60 hours in simulated time. We then calculated the axis lengths of each aggregate using the MATLAB function *ellipsoid_fit* which fits an ellipsoid surface to a set of three-dimensional points (in our case, this is the 10,000 particles and their positions) [22]. The dimensions of these bodies then allows us to determine if Haumea's shape is a Jacobi ellipsoid.

Preliminary Results and Discussion: We have completed simulations of the three different scenarios; all aggregates have average density ~ 2.6 g/cm^3, total mass of about 4.006×10^{21} kg, and rotation period of 3.9153 hours. So far, when we start with spherical aggregates, we are only able to form Maclaurin spheroids (Figure 1). It is interesting that although we did not form Jacobi ellipsoids, the c/a ratios of the aggregates for each scenario are different (Table 1). From S1, the c/a ratio increases by 11% to S2 while the ratio decreases by 11% to S3. This implies that when modeling Haumea's shape, one must take into account Haumea core and crust compositions, and should not assume that the body is homogeneous. Deviations from homogeneity will affect the axis ratios.

In order to generate the shapes predicted by [7-9], we plan to initialize the aggregates as Jacobi ellipsoids and see how they evolve (i.e., if they remain Jacobi ellipsoids) depending on the applied scenario. [5] utilized pkdgrav to simulate aggregate collisions with the goal of forming a Haumea-like aggregate. Although they were not interested in Haumea's shape, they successfully formed an aggregate with axis ratios similar to those predicted by [9]; this demonstrates that pkdgrav is able to form Jacobi ellipsoids under the right conditions.

Table 1 c/a ratios from literature and our case 1 (different size-particles) scenarios

	[9]	S1	S2	S3
c/a	0.52	0.68	0.75	0.60

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