EQUILIBRIUM FIGURE OF A RAPIDLY ROTATING, DIFFERENTIATED HAUMEA. Steven. J. Desch[1], Emilie. T. Dunham[1] and Sarah. M. Sonnett[2] [1]School of Earth and Space Exploration, Arizona State University, [2]Planetary Science Institute. (steve.desch@asu.edu).

Introduction: Since its discovery, the large KBO Haumea has emerged as one of the most interesting objects in the Solar System, and recent discoveries have increased its intrigue even more. Several lines of evidence suggest Haumea suffered a collision its past.
Spectrally, its surface is largely water ice [1-2], but based on its inferred mass and size, its mean density has been inferred to be ~ 2600 kg m^{-3} [3-6], suggesting a differentiated body with rocky core and icy mantle, whose ice mantle has largely been stripped [7]. Haumea has two moons (Hi'iaka and Namaka) that may have formed from a collisionally produced disk, used to derive a mass 4.006 x 10^{21} kg [8]. Haumea also possesses a collisional family of icy bodies that appear to be fragments of the stripped mantle [7]. Haumea is very rapidly rotating, every 3.915 hours [3-6,9]. Its uniform surface composition and its light curve demand a triaxial ellipsoid shape, and Haumea has been shown to be consistent with a rapidly rotating, uniform-density Jacobi ellipsoid with semi-axes 960 x 768 x 496 km [6], and uniform density 2600 kg m^{-3}.

The fact that Haumea suffered a large collision offers unique opportunities to understand KBO internal structure and the nature of mantle-stripping collisions:

1. KBOs generally are predicted to have surfaces that never became warm enough to overturn or undergo ice-rock differentiation [10]; Haumea, through its exposed mantle and collisional family members, is the only KBO whose interior can be probed. Is the surface pure water ice or does it contain significant silicates or other minerals?
2. Other, smaller, asteroids are also triaxial in shape, but may be supported in part by internal strength or granular physics. Granular physics is predicted to play a role on Haumea [11], and would be demanded if Haumea could be shown to depart from hydrostatic equilibrium.
3. Collisional families in the asteroid have been subject to orbital evolution and dispersion, but Haumea's collisional family in the Kuiper Belt largely preserves the velocity structure of the collisional fragments [7]. The fragments in Haumea's collisional family have very low velocity dispersion, < 0.1 km/s, with implications for how mantle stripping events occur. These insights would be relevant to the mantle-stripped asteroid 16 Psyche [12] and the Psyche mission [13].

Probing the interior structure of Haumea, and inferring the mechanics of the collision, require good knowledge of Haumea's size, shape, and surface albedo. All of these quantities must now be updated, thanks to the observational campaign that yielded the size and shape of Haumea's shadow on Earth as it occulted an 18^{th}-magnitude star in January 2017 [9]. The projection of Haumea on the plane of the sky was found to be an ellipse with semi-axes a' = 852 (±2) and b' = 569 (±13) km. The semi-axes of Haumea were inferred to be 1161 (±30) x 852 (±4) x 513 (±16) km [9]. From these larger axes, a maximum bulk density of 1885 kg m^{-3} was inferred, much lower than previous estimates. It was inferred that Haumea cannot be a simple fluid in hydrostatic equilibrium, and support by granular physics [9,11] was invoked. Surprisingly, Haumea was also observed to have a thin ring, in the same orbital plane as Hi'iaka, and presumably in Haumea's equatorial plane [9].

Our goal here is to reconcile these new results from the occultation campaign with the previous results. We employ a code we have written to calculate the shape of a rapidly rotating, differentiated Haumea, to answer the following questions. What are Haumea's true axes? Is Haumea's surface pure water ice? Is it supported in part by granular physics, or is it a traditional fluid in hydrostatic equilibrium?

Methods: We model the structure of Haumea using a code we have written, based on [14], that calculates the figure of equilibrium of a non-axisymmetric body rapidly spinning in solid-body rotation. We employ a simplified equation of state: $\rho = 0$ for $P < 0$, $\rho = \rho_{ice} = 921$ kg m^{-3} for $0 < P < P_{cmb}$, and $\rho = \rho_{rock}$ for $P_{cmb} < P$. Here P_{cmb}, the pressure at the core-mantle boundary (CMB), and ρ_{rock}, the density of the rocky core, are adjustable variables. This treatment imposes uniform pressure at the CMB. The algorithm allows for self-compression, but we neglect it because it makes < 1% difference in the results. We fix the a and b axes of the body (rotation is about the c axis), and find solutions consistent with Haumea's mass and rotational period. Despite being differentiated into rocky core and icy mantle, the solutions are generally an outer surface that is a triaxial ellipsoid, and a CMB that is a triaxial ellipsoid with similar axis ratios.

We then calculate the elliptical projection of the outer surface on the plane of the sky, assuming the tilt of Haumea's pole with respect to the plane of the sky is ι, and its rotational phase is ψ, where ψ=0° if Haumea's a axis points toward Earth during the occultation. These angles are constrained by the orientation of Haumea's ring and Hi'iaka's orbit during Haumea's 2017 occultation to be ι ≈ 13.6° [9], but increasing from close to 0° in 2004 [3]. As Haumea's rotational pole has pointed away from Earth as Haumea has orbited, the amplitude Δm of Haumea's light curve (which depends on its tilt and its axis ratios [3], as well as its surface reflectivity) has decreased. A goal is to match the amplitude Δm at different epochs. Haumea's rotational phase is constrained by its light curve; [9] claim ψ ≈ 0° during the occultation, but from inspection of the light curve, ψ ≈ 18° appears to be favored.

Results: We find several solutions that conform to all the constraints, including Haumea's mass and rotational period. We currently favor the following solution. The semi-axes of Haumea's outer surface are 1000 x 825 x 523.2 km, with axis ratios b/a = 0.825 and c/a = 0.523. Haumea's core has semi-axes 915 x 760 x 488 km, with axis ratios b_c/a_c = 0.831 and c_c/a_c = 0.534. The thickness of the ice mantle is 85 km, 65 km, and 35 km, along the a, b, and c axes, respectively. The core density is 2599 kg m^{-3} and Haumea's average density is 2216 kg m^{-3}. The pressure at the CMB is 18 MPa. Ice makes up 23% of the volume, and 10% of the mass, of Haumea.

Imposing an orientation ι = 13.6°, the best fit to the shadow uses ψ = 21.7° and yields a'=852.0 km and b'= 556.7 km, an excellent (< 1σ) fit. The optimal orientation has ι = 16.1°, the best fit to the shadow uses ψ = 21.5°, and yields a' = 851.9 km and b' = 569.2 km, an exact fit.

A fit to the light curve requires better modeling of the reflectance function, but appears to be potentially consistent with Haumea's light curve. Previously Haumea's albedo was estimated at about p_v = 0.726, assuming axes 980 x 759 x 498 km [3]. Using our preferred axes 1000 x 825 x 523 km, we infer a lower albedo, p_v = 0.66.

Discussion: The occultation observations of [9] make clear that Haumea is larger than previously thought, meaning it is also lower in density and darker in albedo. But our results suggest that Haumea need not be as large as [9] claim. Our preferred axes (1000 x 825 x 523 km) lie between previous estimates (980 x 768 x 496 km) and those of [9] (1161 x 852 x 513 km). Our inferred average density (2216 kg m^{-3}) lies between previous estimates (2600 kg m^{-3}) and those of [9] (1885 kg m^{-3}). Interestingly, we generally find that Haumea's core must have density 2600 - 2700 kg m^{-3}, close to previous estimates for Haumea's bulk density. This is consistent with previously proposed scenarios in which Haumea's core is hydrated silicate, formed by aqueous alteration during hydrothermal circulation through a cracked core [15].

Previous analyses [1] have suggested that Haumea's surface is a mix of about 81% H_2O ice and 19% bluish phyllosilicates like kaolinite. Other analyses suggest a more nearly pure H_2O ice surface [2]. We suggest that a reduction in Haumea's albedo relative to previous estimates means its ice mantle must contain impurities, possibly >10% phyllosilicates. This would be consistent with formation scenarios [15].

In contrast to the conclusion of [9], we find that there is no need to invoke granular physics to explain the shape and size of Haumea inferred from the occultation. Haumea appears consistent with a fluid body in hydrostatic equilibrium.

Next Steps: We propose to undertake a systematic search of parameter space to find more solutions of rapidly rotating fluid bodies in solid-body rotation, consistent with Haumea's mass, rotational period, and shadow. By including more information about its moons and rings, and including realistic reflectance laws, we expect to be able to fit Haumea's light curve and albedos as well. We will use this information to improve estimates of Haumea's internal structure, its thermal evolution, and the origin of Haumea and its collisional family.

References: [1] Trujillo, CA, Brown, ME, Barkume, KM, Schaller, EL and Rabinowitz, DL (2007) *ApJ* 655, 1172-1178; [2] Pinilla-Alonso, N, Brunetto, R., Licandro, J., Gil-Hutton, R, Roush, T and Strazzulla, G (2009) *A&A* 496, 547-556; [3] Rabinowitz, DL, Barkume, KL, Brown, ME, Roe, H, Schwartz, M, Tourtellotte, S and Trujillo, CA (2006) *ApJ* 629, 1238-1251; [4] Lacerda, P and Jewitt, DC (2007) *AJ* 133, 1393; [5] Lellouch, E et al. (2010) *A&A* 518, L147-151; [6] Lockwood, AC, Brown, ME and Stansberry, J (2014) *EM&P* 111, 127-137; [7] Brown, ME, Barkume, KM, Ragozzine, D and Schaller, E (2007) *Nature* 446, 294-296; [8] Ragozzine, D and Brown, ME (2009) *AJ* 137, 4766-3776; [9] Ortiz, JL et al. 2017) *Nature* 550, 219-223; [10] Desch, SJ, Cook, JC, Doggett, TC and Porter, SB (2009) *Icarus* 202, 694-714; [11] Holsapple, KA (2007) *Icarus* 187, 500-509; [12] Asphaug, E and Reufer, A (2014) *Nature Geosci.* 7, 564-568; [13] Elkins-Tanton, LT et al. (2017) LPSC 48, #1718; [14] Hachisu, I (1986) *ApJS* 62, 461-499; [15] Desch, SJ & Neveu, M (2015) LPSC 46, #2082.