THE BLACK SHEEP OF HAUMEA'S COLLISIONAL FAMILY. Jason C. Cook[1], Steven J. Desch[2], and Mark Rubin[2]. [1] NASA Ames Research Center, Moffett Field, CA, 94035, USA. [2]School of Earth and Space Exploration, Arizona State University, PO Box 1404, Tempe AZ, 85287-1404, USA. (steve.desch@asu.edu).

The Kuiper Belt Object (KBO) Haumea (née 2003 EL_{61}) is a unique object in the solar system, especially since it is the only KBO to which a collisional family is associated. The inference of a large collision and a collisional family comes from many lines of evidence. Haumea's light curve indicates a very rapid rotation (3.9 hr), a shape consistent with a Jacobi ellipsoid with radii 980 x 759 x 498 km and density $\approx 2.6\,\mathrm{g\,cm^{-3}}$, and an albedo $p_{\rm V} \approx 0.70 - 0.75$ [1,2]. This rapid rotation was probably imparted by an oblique collision. It has two moons, Hi'iaka and Namaka, which themselves could have formed by collision, in the same manner that Pluto's moon formed [3]. Fits to their orbits and mutual interactions yield masses of 4.006×10^{24} g for Haumea [3] (consistent with the light curve estimates), and 1.79×10^{22} g for Hi'iaka and 1.79×10^{21} g for Namaka [4]. From its high density, Haumea is inferred to be mostly rock, despite its high albedo and near-infrared (NIR) reflectance spectrum, which indicate a surface of nearly pure water ice [5]. Assuming a mean density $\bar{\rho} = 2.584\ \mathrm{g\,cm^{-3}}$, a density of rock $\rho_{\rm r} = 3.25\,\mathrm{g\,cm^{-3}}$, and a density of ice $\rho_{\rm ice} = 0.935\,\mathrm{g\,cm^{-3}}$ (see [6]), a rock fraction $(1 - \rho_{\rm i}/\bar{\rho})/(1 - \rho_{\rm i}/\rho_{\rm r}) = 90\%$ can be inferred. The high density in particular led [7] to conclude that a collision stripped Haumea of its icy mantle after it had differentiated. A radius of 830 km for the proto-Haumea has been inferred, implying Haumea lost $\approx 16\%$ of its mass in the collision; based on energetics, a radius ≈ 500 km was inferred for the impactor [8]. The strongest evidence for a collision is, of course, the existence of a collisional family. Some 9 other KBOs with similar icy surfaces and orbital elements have been identified as a collisional family of Haumea, ejected during the collision [8-10]. The dispersion of their orbits is consistent with the collision occurring several Gyr ago [9]. It has been argued [11] that both bodies were Scattered Disk objects that collided not long after the 2:1 resonance crossing that formed the modern Kuiper belt, about 3.9 Gyr ago. This collisional family, unique in the solar system, can be used to probe the evolution of the Kuiper belt and the collision that reshaped Haumea, especially as more members are found. Here we propose that the current criteria for membership have been too restrictive, and that many already-discovered KBOs may be "black sheep" of Haumea's collisional family.

There are currently only 9 accepted [8-10] members of Haumea's collisional family (besides Haumea itself). In roughly decreasing order of mass these are: 2002 TX_{300}, 2003 OP_{32}, 2005 RR_{43}, 1996 TO_{66}, 1995 SM_{55}, 2005 CB_{79}, 1999 OY_3, 2003 UZ_{117} and 2003 SQ_{317}. All were selected as family members because of their proximity to each other in orbital space and because of their nearly identical water ice surfaces. Their orbits are consistent with ejection from the proto-Haumea at speeds $< 150\,\mathrm{m\,s^{-1}}$ [10], and all have photometric colors or visible/NIR spectra consistent with water ice [8,10]. Several groups [8,10] have emphasized the need to select family members using both of these criteria, to weed out interlopers in the orbital space, but there are hints that this approach is missing many family members. First, the total mass of the family members (excluding Haumea) is low. Using absolute magnitudes H from the Minor Planet Center database (`http://www.minorplanetcenter.org/iau/lists/TNOs.html`), and the conversion $M = 1.061 \times 10^{24}\, p_V^{-3/2}\, 10^{-0.6H}$ g and assuming an icy albedo $p_V = 0.7$ yields a combined mass of 5.11×10^{22} g for these KBOs, dominated by 2002 TX_{300}. Adding the icy moons Hi'iaka and Namaka to this list increases the mass of known icy fragments only to 7.08×10^{22} g, which is $< 2\%$ of Haumea's mass, much less than even the mass loss estimated by [8]. Clearly more family members remain to be discovered. More significantly, all the icy collisional family members observed so far have very low inferred ejection velocities, $< 150\,\mathrm{m\,s^{-1}}$, much lower than the escape speed from Haumea, $\approx 860\,\mathrm{m\,s^{-1}}$. The mismatch has motivated development of multiple-event scenarios [12] to explain the lack of identified family members ejected at higher velocities.

Here we propose that Haumea's collisional family should include significantly more members, including roughly equal numbers of icy bodies and bodies that are rock/ice mixtures that appear as "normal" KBOs. Our hypothesis is based on simulations by [6] that show that KBOs with radii in the range 500 - 1000 km only *partially* differentiate, forming a rocky core and icy mantle surrounded by a thick crust of rock/ice mixture that never reached temperatures high enough to melt or differentiate. Ejection of the icy mantle necessarily ejects this crust as well; fragments of the crust should appear spectrally similar to each other, and probably will resemble "normal" KBOs in other respects. Given the inferred geometry of the collision, we consider it likely that these crustal fragments would have been ejected at higher velocities, on average, than the icy fragments. A second population of collisional family members, ejected from the crust at higher speeds, and spectrally similar to normal, undifferentiated KBO surfaces, could help resolve the problems with both the missing mass and the low ejection speeds. Here we calculate the number of these non-icy members of Haumea's collisional family, and suggest candidate members.

We begin by estimating the size of the proto-Haumea and impactor. We infer Haumea's present-day mass of rock to be 3.59×10^{24} g, and its ice mass to be 0.42×10^{24} g. Assuming the impactor core contributes $\sim$ 10% to that total, the proto-Haumea must have had a core $\sim 3.2 \times 10^{24}$ g and a radius 616 km. To model this body, we have run the KBO thermal evolution code developed by [6] to account for the time evolution of KBOs heated by long-lived radionuclides only, and including the effectives of a small percentage (5%) of ammonia in the ice. We find that the estimated initial core mass develops in a KBO with density $2.0\,\mathrm{g\,cm^{-3}}$ and radius 850 km, so we adopt these parameters for the proto-Haumea. By $t = 1\,\mathrm{Gyr}$ after formation, this body will have differentiated into a rocky core of mass 3.21×10^{24} g, an icy mantle with mass 1.06×10^{24} g, and and an undifferentiated crust of mass 0.87×10^{24} g. (The differentiation is nearly complete at $t = 650\,\mathrm{Myr}$, when the rocky core and ice layers are only $\approx$ 2% smaller, and the crust only $\approx$ 5% larger, so our conclusions are little changed if the collision takes place any time after the formation of the scattered Kuiper belt.) For the impactor, we assume a smaller body with density $2.0\,\mathrm{g\,cm^{-3}}$ and radius 450 km and mass 0.763×10^{24} g. It differentiates in $< 600\,\mathrm{Myr}$ to form a rocky core with mass 0.37×10^{24} g, an ice mass 0.12×10^{24} g, and a crust mass 0.27×10^{24} g. In analogy with the Earth-Moon impact [13], we assume that the cores of the impactor and proto-Haumea merge after the impact. (Our conclusions are not qualitatively changed if they do not merge, and the impactor's core instead is lost.) Their combined mass of rock, 3.58×10^{24} g, matches the mass of rock inferred to be in Haumea today. The combined masses of ice and crust are 1.18×10^{24} g and 1.14×10^{24} g, respectively.

These masses are to be compared with the known family members. The combined mass of the known (icy) family members is $< 6\%$ of the amount of ice we predict was ejected. Either observations have so far discovered only 5% of the family members, or many of the family members have diffused out of the collisional family, or both. We also predict that there should be as much mass in non-icy members as in icy members and that observations should have *already* found at least ≈ 10 non-icy members of the collisional family. Out of the 27 candidates at low velocity dispersion δv identified by [9], or the list of 35 compiled by [10], no more than half of the objects are likely to be interlopers, and 30-40% are likely to be non-icy members, we predict.

2005 UQ_{513} is notable for being rejected [9,13] despite its very low dispersion ($\delta v = 31\,\mathrm{m\,s^{-1}}$) and the detection of some ($18 \pm 7\%$) water ice on its surface [14]. 2005 UQ_{513} fits the properties of a rock/ice crustal fragment. Remarkably, several other candidates have visible gradients [8,9] consistent with that of 2005 UQ_{513}, $18.1 \pm 2.0\%$ (per 100 nm). The candidates 2000 CG_{105} ($6.7 \pm 17.5\%$), 1999 OH_4 ($20.2 \pm 35.6\%$), 1998 HL_{151} ($18.1 \pm 16.9\%$), 1998 WT_{31} ($16.6 \pm 5.2\%$), 1999 RY_{215} ($4.54 \pm 6.65\%$) and 2004 SB_{60} (spectrally featureless) have all been rejected because their photometric colors are inconsistent with *pure* ice, but we suggest they may all be fragments of the proto-Haumea's crust, and may be the "black sheep" of Haumea's collisional family.

References: [1] Lacerda, P. & Jewitt, D. AJ 133, 1393, 2007. [2] Lellouch et al. A&A 518, 147, 2010. [3] Canup, R. Science 307, 546, 2005 [4] Ragozzine, D. & Brown, M. AJ 137, 4766, 2009. [5] Barkume, K., Brown, M. & Schaller, E. ApJ 640, 87, 2006. [6] Desch, S., Cook, J., Doggett, T. & Porter, S. Icarus 202, 694, 2009. [7] Brown, M., et al., ApJ 639, 43, 2006 [8] Brown, M., Barkume, K., Ragozzine, D. & Schaller, E. Nature 446, 294, 2007. [9] Ragozzine, D. & Brown, M. AJ 134, 2160, 2007. [10] Snodgrass, C., Carry, B., Dumas, C. & Hainaut, O. A&A 511, A72, 2010. [11] Levison, H., Moribidelli, A., Vokrouhlicky, D. & Bottke, W., AJ 136, 1079, 2008. [12] Schlichting, H. & Sari, R., ApJ 700, 1242, 2009. [13] Canup, R., Icarus 168, 433, 2004. [14] Pinilla-Alonso, N., Licandro, J. & Lorenzi, V., A&A 489, 455, 2008. [15] Barkume, K., Brown, M. & Schaller, E., AJ 135, 55, 2008.