THE CASE OF THE MISSING CERES FAMILY.

A. S. Rivkin[1] and E. Asphaug[2], [1]JHU/APL, Laurel, MD, USA (andy.rivkin@jhuapl.edu). [2]Arizona State University, Tempe, AZ, USA.

Introduction: Most of the largest asteroids in the main belt are associated with an impact-generated dynamical family. The Vesta family dominates the inner asteroid belt with its numbers [1-2], and was a critical piece of evidence in tying the HED meteorites to Vesta. In addition to Vesta (the third-largest asteroid), Pallas (the second-largest asteroid), Hygiea (the fourth-largest asteroid), and the largest S-class asteroid, 15 Eunomia, all have dynamical families [3-6].

Twelve asteroids in the current main belt have diameters over 250 km, containing two-thirds of the asteroid belt's mass. In addition, [7] estimated that two of the largest present-day families, Themis and Eos, had parent bodies in the ~300-400 km size range where we find Hygiea, Pallas, and Vesta today. In total, ten of the 14 known 250+ km bodies in the past or present asteroid belt are associated with dynamical families, either of the smaller "cratering" type, dominated by a major body and relatively small fragments, or large disruptions (impact energy $Q > Q^{*}_{D}$) that indicate gravity-dominated catastrophic events. It is curious, then, that the very largest body in the asteroid belt, Ceres, is missing from this list of parents.

Ceres is unassociated with any sort of family at all as far as we know. This alone is perhaps not sufficient to draw any conclusion, but motivates us towards the considerations we make here. We hope to show that the lack of a family has implications for Ceres' internal structure, and further hope to encourage research beyond the scope of this work – geodynamical, chemical and collisional modeling – that can provide additional firm constraints.

Hiding out? Could the Ceres family be hiding somewhere? It could be argued that the size limit of a Ceres family is smaller than what has been catalogued in the main asteroid belt. However, that seems unlikely. The limiting absolute magnitude for completeness in the Minor Planet Center database is $H \approx 15$ for the middle asteroid belt where Ceres resides [2], corresponding to a threshold diameter of ~ 4 km for objects with Ceres-like albedo. For comparison, the second-largest members of the Pallas, Vesta, and Sylvia families have diameters in the 10-25 km range, and many of the other families containing asteroids with diameters >250 km also contain additional asteroids with diameters of 75 km or larger. For comparison, the family associated with 128 Nemesis, a C-class asteroid near Ceres' location in the middle asteroid belt has over 250 identified family members with $H \leq 15$ [4]. *If a Ceres family exists, it is exceedingly unlikely to have escaped detection.*

Dodging bullets? Could Ceres have simply avoided making a family? Given that it is the largest asteroid, and thus the biggest target, it is exceedingly unlikely that it would have avoided impact by a sizable smaller asteroid. However, it might be argued that the escape speed for Ceres, ~0.5 km/s, would suppress family formation, as it is higher than that of any other body in the asteroid belt. The amount of ejecta escaping from Ceres might be reduced, compared to similar-sized impacts occurring on lower-gravity asteroids; and the energy required to escape might lead to highly comminuted fragments or even vaporization.

Assuming Ceres and Vesta have experienced a comparable bombardment, Ceres' greater escape velocity should lead to a smaller amount of ejecta escaping, roughly 2/3 what would escape Vesta. Half as much would escape Ceres as Pallas, and only 1/4 as much as Hygiea, for a similar impact event, leading to the expectation of a less prominent family for Ceres. However, while the amount of escaping ejecta from a given impact event may be reduced, this is more than made up for by Ceres experiencing more massive as well as more frequent impact events. For example, the model of [8] predicts 2.5 impacts of 40-km bodies into Vesta over 4.5 Gy, implying 7-8 similarly-sized impacts into Ceres over the same time period. [9] simulated the cratering rate on Ceres and Vesta, providing comparable results. They find that the largest expected impactor on Ceres is ~70 km in diameter (similar in size to the impactor that created the Vesta family [10]), and they expect Ceres to have nearly 50 craters over 100 km in diameter. Interestingly, hints of surface features consistent with impact basins of the sizes expected are found in HST- and AO-derived albedo maps of Ceres [11-12]. Two particularly large albedo features (diameters 180 and 350 km) are interpreted as impact basins by [12], and the latter feature in particular is consistent with a family-forming size based on the impact scaling. The larger feature is also comparable to the size one would expect for a 70-km impactor hitting Ceres at 5 km/s (400-500 km final diameter, consistent with the estimates of [9]. *Given all of this, there is no obvious impediment to creating a Ceres family.*

Collisional or dynamical erosion? Just as collisions create families, so they eventually destroy them. Given enough time, the members of a collisional family will be ground down. It may be argued that the current lack of a Ceres family is simply a consequence of timing and inevitable erosion rather than providing insight into Ceres itself. [8] modeled the collisional and dynamical evolution of the asteroid belt as a whole, and found the collisional lifetime of 1-km bodies approached 1 Gyr. This collisional lifetime estimate suggests that a sizable fraction of 1-km and larger objects in any Ceres family should still exist regardless of when an impact took place.

Nor should drift due to Yarkovsky forces play a major role in the removal of km-scale Ceres family objects. The nearest strong resonance, the 5:2 mean motion resonance with Jupiter, is at 2.82 AU. This is about 500 Myr away at the quoted, ideal drift rates for 1-km objects [8]. However, the diurnal Yarkovsky drift will either shrink or expand orbits depending upon whether an object is a retrograde or prograde spinner and therefore only half of the objects could be expected to move toward the 5:2 resonance, with half moving away from it. Taking this into account, and noting the quoted rate is a maximum rate, and that larger objects will drift more slowly, it seems unlikely that a Ceres family can be removed *in toto* via drift to a resonance and subsequent evolution to planet-crossing behavior. *If a Ceres family is created, and it is like other asteroid families in its nature, it is unlikely to have been erased.*

Sublimation of an icy family? It is also possible that rather than suffering collisional or dynamical erosion, any once-existing Ceres family experienced sublimation. Ceres' shape and moment of inertia have been interpreted as indicating an ice shell above a rocky core [13], in agreement with thermal evolution models [14-15]. However, the surface of Ceres is too warm to maintain ice for significantly long periods of time (save very near the poles), and the retreat rate of ice does not reach m/Gy speeds until it reaches a depth of order ~100-1000 m (depending upon latitude and surface temperature) beneath an insulating lag deposit [16-17].

To first order, an icy Ceres family is subject to the same sublimation rates as Ceres itself. Can its members have simply sublimed away? *An order-of-magnitude argument shows that sublimation may have been a powerful force in erasing an icy Ceres family, this simplified model very likely understates the case for sublimation.*

To estimate the likely temperatures for icy Ceres family members, we turn to the icy satellites, with well-known geometric and Bond albedos [18]. Using the Bond albedo for Ganymede results in average equatorial temperatures in the 150-160 K range, at which even a 100-km body would have only 5% mass remaining after 200 My. Sub-solar temperatures are even higher, approaching 210 K. This is noteworthy because Ganymede is not a low-albedo object (geometric albedo 0.6, bond albedo 0.42), and is thought to have only a few tens of percent of non-ice material at its surface at most (Hibbitts, personal communication).

While cometary sublimation eventually ceases due to lag deposit generation, the relatively clean ice expected in Ceres' mantle provides much less opportunity for material to build up. Sublimation also provides a plausible mechanism for preventing lag deposit formation in the first place on members of a Ceres family as gas flow removes particles. A 20-km body with Ganymede's albedo at 2.77 AU can eject 160-μm diameter grains at its equator. At ±30^{o} and poleward latitudes, only 1-10-μm grains can be ejected, but if a lag deposit were begun, it should darken and warm by 5-10 K on the timescale of 10-100 My, perhaps leading to outbursts at those latitudes as increased gas flux can eject more massive particles. Smaller bodies, with less gravity, can eject potential lag deposit particles even at higher latitudes and lower temperatures. This admittedly simplistic view ignores the effects of obliquity, shape changes, volumetric changes as ice heats and cools, and other factors, but those should not change the overall conclusion. Indeed, shape changes conceptually could lead to additional stresses on small objects, which in turn could lead to fracturing that would aid the sublimation process, and non-zero obliquity would increase the fraction of the body experiencing sub-solar temperatures and increase the overall sublimation rate.

References: [1] Binzel R. P. and Xu S. (1993) *Science, 260*, 186-191. [2] DeMeo F. and Carry B. (2013) *Icarus, 226,* 723-741. [3] Gil-Hutton R. (2006) *Icarus, 183,* 93-100. [4] Nesvorny D. (2012) *NASA Planetary Data System*. [5] Carruba V. (2013) *Mon. Not. Royal Ast. Soc., 431,* 3557-3569. [6] Mothé-Diniz T. et al. (2001) *Icarus, 152,* 117-126. [7] Durda D. D. et al. (2007) *Icarus, 186,* 498-516. [8] O'Brien D. P. and Greenberg R. (2005) *Icarus, 178,* 179-212. [9] de Elía G. and Di Sisto R. (2011) *arXiv preprint* 1109.2523. [10] Asphaug E. (1997) *Met. Plan. Sci. 32,* 965-980 [11] Li J.-Y. et al. (2006) *Icarus, 182,* 143-160. [12] Carry B. et al. (2008) *Astron. Astroph., 478,* 235-244. [13] Thomas et al., 2005 [14] McCord T. B. and Sotin C. (2005) *JGR, 110,* 5009-5011. [15] Castillo-Rogez J. C. and McCord T. B. (2010) *Icarus, 205,* 443-459. [16] Fanale F. P. and Salvail J. R. (1989) *Icarus, 82,* 97-110. [17] Schorghofer N. (2008) *Ap. J., 682,* 697-705. [18] Castillo-Rogez J. (2012), *The Science of Solar System Ices*, Springer.