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The case of the missing Ceres family

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ABSTRACT

Ceres is unusual among large (>250 km) asteroids in lacking a dynamical family. We explore possible explanations, noting that its particularly large size and the ubiquity of families associated with other large asteroids makes avoidance of a sufficiently-sized collision by chance exceedingly unlikely. Current models of Ceres' thermal history and interior structure favor a differentiated object with an icy near-surface covered by an ~0.1–1 km lag deposit, which could result in a collisional family of diverse, predominately icy bodies. We predict that sublimation of an icy Ceres family would occur on timescales of hundreds of millions of years, much shorter than the history of the Solar System. Sublimation on a Ceres family body would be aided by a low non-ice fraction and a high average temperature, both of which would inhibit lag deposit development. Because there seems to be no likely mechanism for removing a rocky Ceres family, and because the formation of a Ceres family of some kind seems nearly statistically inevitable, the lack of a Ceres family is indirect but independent evidence for Ceres' differentiation.

All of the other large asteroids lacking dynamical families (704 Interamnia, 52 Europa, and 65 Cybele) have spectral properties similar to Ceres, or otherwise suggesting ice at their surfaces. While other large asteroids with similar spectral properties do have families (24 Themis, 10 Hygiea, 31 Euphrosyne), their families are not well understood, particularly Hygiea.

1. Background

1.1. Motivation: the dynamical families of large asteroids

The asteroid belt is littered with members of dynamical families. Since their first identification over a century ago (Hirayama, 1918), these families have proven central to our understanding of the formation and evolution of the Solar System, to the delivery of meteorites to Earth, and the nature of the impact hazard.

Most of the largest asteroids in the main belt are associated with an impact-generated dynamical family (Table 1). The Vesta family famously dominates the inner asteroid belt with its numbers (Binzel and Xu, 1993; DeMeo and Carry, 2013), and was a critical piece of evidence in tying the HED meteorites to Vesta. Pallas, the second-largest asteroid, has a dynamical family (Gil-Hutton, 2006), Hygiea, the fourth-largest asteroid, is associated with a family (Nesvorny, 2012; Carruba, 2013; Mothé-Diniz et al., 2001, see Section 3.2 for further discussion of the Hygiea family), as is the largest S-class asteroid, 15 Eunomia (Nesvorny, 2012).

There are 12 asteroids in the main belt with diameters over 250 km, containing two-thirds of the asteroid belt's mass. In addition, Durda et al. (2007) 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. Along with the Themis and Eos family parent bodies, then, we know of 14 bodies in the asteroid belt that are or once were over 250 km in diameter. Ten of these 14 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 $Q > Q^*_D$, defined as the specific impact energy per colliding mass required to result in a largest remnant asteroid equal to half the original target mass) that indicate gravity-dominated catastrophic events (e.g. Durda et al., 2007). It is curious, then, that the largest body in the asteroid belt, Ceres, is missing from this list of parents.

Ceres is unassociated with any sort of family at all in our current understanding of dynamical groupings, which alone is perhaps not sufficient to draw any conclusion, but motivates us towards the considerations we make in this paper. 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 paper

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Table 1
Asteroids over 250 km diameter are by and large associated with dynamical families. The objects that are not, found in italics, share certain spectral properties: All are members of the C or X spectral complexes of Bus and Binzel (2002), and none have 3-μm band shapes like Pallas. The "3-μm Type" displays both the Rivkin and Takir taxon names. "NA" means the object was not observed in either or both surveys. A blank 3-μm entry indicates the asteroid is of the S or V spectral types.

Object	Family?	D (km)	Tax	3-μm Type	Semi-major axis (AU)
1 Ceres	N	952	C	*Ceres/Ceres*	2.765
2 Pallas	Y	544	B	Pallas/Sharp	2.772
4 Vesta	Y	525	V		2.361
10 Hygiea	Y	431	C	Ceres/Ceres	3.140
704 Interamnia	N	326	B	*Varies/Sharp*	3.060
52 Europa	N	315	C	*Themis/Europa*	3.011
511 Davida	Y	289	C	Pallas/Sharp	3.166
65 Cybele	N	273	X	*Themis/NA*	3.427
87 Sylvia	Y	286	X	NA/NA	3.488
15 Eunomia	Y	268	S		2.643
3 Juno	Y	258	Sk		2.671
31 Euphrosyne	Y	256	Cb	Themis/Europa	3.154
Themis parent	Y	~369	B	Themis/Rounded	3.13
Eos parent	Y	~260	K		3.01

– geodynamical, chemical and collisional modeling – that can provide firm constraints.

1.2. Why might we expect a Ceres family?

It was once thought that Ceres did have a family. Williams (1992) included a Ceres family as #67 in his compendium, though even at that time he noted the seeming implausibility of several S- and M-class asteroids being associated with the presumed-intact C-class asteroid Ceres. Zappalà et al. (1995) found Ceres to be at the edge of its own family using one family identification method, and excluded it from the equivalent Minerva family using the other method. Migliorini et al. (1995) excluded Ceres from its own family, renaming it the Gefion family after the next-largest member 1272 Gefion. Similarly, Bus (1999) did not find a spectro-dynamical family associated with Ceres, and Mothé-Diniz et al. (2005) concurred, also identifying the nearest family to Ceres, dominated by S asteroids, with the asteroid Gefion. Studies of asteroid families in the past decade have not included a Ceres family, and a very recent study by Milani et al. (2014) found no Ceres family in a sample of over 330,000 asteroid proper elements, specifically noting and discussing its absence.

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 (DeMeo and Carry, 2013), corresponding to a threshold diameter of ~4 km for objects with Ceres-like albedo $p_v \sim 0.07$, and smaller for brighter objects. 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. The family associated with 128 Nemesis, a C-class asteroid near Ceres' location in the middle asteroid belt, has nearly 150 members 4 km and larger identified in the WISE dataset (Masiero et al., 2013), with over 250 present in the Nesvorny (2012) Nemesis family dataset with $H \leqslant 15$.

Any present-day family associated with Ceres would need to be composed entirely of objects so small that they have so far eluded detection (that is, a few km diameter), while most other large asteroids, and many small ones, have collisional families that have dozens of confirmed members. Since it seems unlikely that an existing present-day Ceres family would elude detection, we now turn to hypotheses that can explain its absence.

1.3. Dodging bullets

Could Ceres have simply avoided a family-forming impact? 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, as we discuss in further detail below. However, it might be argued that the escape speed for Ceres, ~0.5 km/s, would suppress family formation, being so much 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.

Here we consider the first of these, and estimate the total expected ejecta mass by applying scaling models (Housen and Holsapple, 2011) for impact ejecta produced by hypervelocity impacts into asteroidal targets. In order to simplify the analysis, and to make it comparable to previous related work, we follow the approach of Jewitt (2012), who studied whether comet-like activity in active asteroids (also called "main belt comets") could be the result of ejecta produced by impact cratering. We adopt the same scaling models for ejecta production, to obtain expected values for ejecta production from impacts into Ceres-like targets.

The cumulative mass of ejecta m_e moving faster than a given speed v following a hypervelocity impact event into a planar target is observed to follow a power-law relationship to the ratio of v to impactor speed U,

$$m_e/M = A(v/U)^{\alpha} \tag{1}$$

where A is a constant, assumed ~0.01 in Jewitt (2012) after Housen and Holsapple (2011), which we adopt here, and $\alpha = -1.5$ for a range of materials, where M is the mass of the projectile. Impact velocity U is typically taken as 5 km/s in the main asteroid belt (e.g. Bottke et al., 1994), although high-inclination bodies like Pallas may have larger impact speeds by a factor of 2. For Ceres we adopt the nominal value U = 5 km/s.

To test whether Ceres could be biased by its larger gravity against producing a detectable asteroid family, we hold M constant for now (e.g. assume it gets hit by the same bombardment as other large asteroids), and set v equal the escape speed of the target, $v_{esc} = r\sqrt{8\pi G\rho/3}$. This gives the relative amount of potential family-forming material m_e escaping an event of the same M and U, for given scaling and material properties A, α and ρ.

According to the scaling, $m_e \propto v_{esc}^{\alpha} \propto r^{-1.5}$, and consequently less ejecta escapes per event, in larger targets. Assuming Ceres and Vesta have experienced a comparable bombardment (same M) then the greater escape velocity of Ceres ($v_{esc} \sim 0.5$ km/s)