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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) should lead to a smaller amount of ejecta escaping Ceres, reduced to roughly 2/3 what would escape Vesta. Half as much would escape Ceres as Pallas, and 1/4 as much as Hygiea, for a similar impact event, leading to the expectation of a less prominent family.

However, Ceres has a lower ρ compared to many large asteroids, which lowers its escape speed, so the above calculation underestimates the ejecta from Ceres relative to Vesta. More important, the largest likely impact into Ceres, M, will be larger than for other asteroids, in proportion to the asteroid's greater cross section, πr^2. Convolving the increased likelihood of an impact of given mass M with the ejecta fraction escaping from the target, one finds the product goes instead as $\sqrt{r}$, i.e., that Ceres should have produced a more massive family than other asteroids, in a given time period.

Thus, while Ceres' higher escape velocity reduces the amount of escaping ejecta from a given impact event, this is more than made up for by the larger body experiencing more massive as well as more frequent impact events. Elía and Sisto (2011) simulated the cratering rate on Ceres and Vesta, finding that the largest expected impactor on Ceres is ~70 km in diameter (similar in size to the impactor that created the Vesta family; Asphaug, 1997), and they expect Ceres to have nearly 50 craters over 100 km in diameter.

More generally, Thomas (1999) found that the great majority of rocky bodies had more than 2 craters with diameters larger than half the body's radius (or larger than ~240 km for Ceres) and half of rocky bodies had a crater with a diameter larger than the body radius. Hints of surface features consistent with basins of this size are found in HST- and AO-derived albedo maps of Ceres (Carry et al., 2008; Li et al., 2006). Two particularly large albedo features (diameters 180 and 350 km) are interpreted as impact basins by Carry et al., and the latter in particular is of a size that could have created a family based on the scaling above. The larger feature is comparable to the size one would expect for a 70-km impactor hitting Ceres at 5 km/s (400–500 km final diameter: Nordyke, 1962; Gault, 1974; Holsapple and Schmidt, 1987) and is also consistent with the Thomas (1999) result.

1.4. Forming a Ceres family: calculations

To explore the likelihood that a Ceres family exists or once existed, we independently calculate the largest impactor that is statistically likely to have struck Ceres over the last 4 Gy of Solar System history.

Using an orbital dataset of 682 main belt asteroids with diameter $D > 50$ km assembled by Farinella and Davis (1992), we can calculate the intrinsic collision probabilities and impact velocities of all of these bodies with Ceres using the methodology of Bottke et al. (1994). This data set is appropriate because $D > 50$ km sizes are reasonably comparable to those that created the Vesta family (Asphaug, 1997). Ceres is assumed to have semimajor axis, eccentricity and inclination values of (2.767 au, 0.108, 9.61 deg), respectively. We find that 634 asteroids in this dataset set were capable of striking Ceres, yielding a collision rate for this population with Ceres of 6.07×10^{-10} yr^{-1}. The average impact velocity is 4.8 km/s, close to the main belt average (Bottke et al., 1994). Note that the projectile size is included in our cross-section calculation; for a few large bodies like Pallas and Vesta, their diameters can substantially modify their individual collision probabilities.

Next, we apply a Monte Carlo code using random deviates to select the timing and size of the impactors hitting Ceres over the last 4 Gy. On average, we find that 2–3 $D > 50$ km bodies have hit Ceres over the last 4 Gy, with one $D > 50$ km body impacting over the last 1.6 Gy. The average size of the impactors over either interval is $D \sim 100 \pm 50$ km. These projectiles are sizable compared to typical impacts in discussions of the collisional evolution of the main belt (e.g., Bottke et al., 2005), but they are small compared to the overall size of Ceres. Still, they may be large enough to make a family; It is thought that the size of the projectile capable of making Vesta's family was on the order of 1/10th the size of Vesta itself (Asphaug, 1997). Our average projectile sizes for Ceres are near the same ratio.

As a way to probe this further, we use a modified version of the fragmentation equations derived in Morbidelli et al. (2009) to calculate the sizes of the largest fragments produced by the average impactors mentioned above. The altered equations are designed to reproduce the nature of the Vesta family for the projectile sizes discussed in Asphaug (1997). They suggest that projectile diameters of $D = 50$, 100, and 150 km yield largest fragments of 8, 17, and 25 km. If we were to use the original Morbidelli et al. (2009) equations, the largest fragments would be even larger. The power-law slopes of the fragment distributions are very steep, much like that observed for the Vesta family (Durda et al., 2007). These calculations reinforce the finding that the average impacts should produce an observable family, yet as noted none is seen.

We can also more quantitatively calculate the likelihood that Ceres goes unimpacted using the Monte Carlo code. In 91% of 10,000 trials, Ceres is hit by at least one 50-km diameter impactor. The most common result is two such impacts (25.5%) with one (21.6%) and three (20.6%) impact scenarios nearly as common. Trials where Ceres is impacted four times (13.3%) and even five times (6.3%) are comparable to the fraction of trials where Ceres goes unimpacted (9.0%). The simulations also return a 99% probability that Ceres was hit at least once with a 30-km impactor (most likely number of such impacts is four) and a 99.5% probability of an impact with a 27.5-km impactor. It is likely at the 90%+ probability level that Ceres suffered a collision large enough to create a family (given our current understanding), and much more likely that it suffered several such collisions than that it suffered none. The Dawn mission to Ceres should be able to detect large basins on Ceres consistent with ~50-km impactors (or confirm the suspected basins mentioned in the previous section) and determine whether the zero-impact case has occurred.

While alternate hypotheses are imaginable, none is more obviously likely than the scenarios presented below in Section 2.3. It is possible that these fragmentation calculations do not apply for Ceres-sized bodies and/or for bodies that have unusual ice-rich upper layers or interiors with oceans, though that does not contradict the implication that a lack of a family is due to such an interior structure as we (and others) suggest below. Consider that the fragmentation equations discussed in Morbidelli et al. (2009) were based on a series of impacts taking place on $D = 100$ km target bodies (Durda et al., 2007). Preliminary hydrocode modeling indicates these results need to be carefully scaled to treat impacts on significantly larger bodies like Vesta or Ceres. Given the paucity of numerical impact experiments onto Vesta- or Ceres-sized bodies, it is possible that we are missing something, and that the true largest fragment is smaller than a few kilometers. The solution to this issue lies in new numerical hydrocode simulations of impacts onto Ceres, which we encourage but are far beyond the scope of this work.

1.5. Impact vaporization and comminution

We can conclude that Ceres is very likely to have been struck by one or more impactors large enough to form a detectable family, in comparison to other asteroids, and therefore now turn to more unusual explanations for the lack of a family. We shift our expectations of Ceres from a "typical" rocky body to one with a structure like those proposed by McCord and Sotin (2005) and Castillo-Rogez and McCord (2010) and consistent with the HST observations of Thomas et al. (2005): a dwarf planet that has differentiated into a near-surface icy shell atop a rocky core. How would that internal structure affect family formation?

One possibility is that a hypervelocity impact into ice, at expected Solar System velocities of 5–10 km/s, might lead to vaporization, or instant fragmentation into pieces so small that they escape detection. The vaporization energy of ice is more than an order of magnitude lower than the vaporization energy of silicates, and the sound speed in ice (about 3 km/s for pure crystalline water, and about 1 km/s for compact glacial ice on Earth) is slower than the sound speed in rocks (about 5 km/s). Thus, as is well known, ice is easier to vaporize by impact shocks than silicates. Could this be the explanation for the missing family?

No, because the most massive escaping materials in an impact, launched just above the escape velocity, are generally subject to low levels of shock. Intense vaporization occurs in the immediate vicinity of a hypervelocity impact, but the escaping Ceres family members (moving >500 m/s) would derive from the outer regions of the transient cavity, from materials accelerated along the flow lines of excavation with decreasing levels of shock intensity. This is why substantial impact melt production is not observed on planetary bodies much smaller than Mars. Indeed, evidence of impact melt on the icy Galilean satellites is limited to the central floors of certain largest craters (and may be endogenic), while the ejecta deposits around craters such as Pwyll on Europa appear rather 'lunar'. Moreover, according to the spallation model (c.f. Melosh, 1989) and in agreement with hydrocode simulations (Asphaug, 1997), some of the most substantial fragments in a family-forming event would be launched promptly by near-surface stress interference and suffer low levels of shock.

It is therefore a relatively obvious but important point, that the largest family members would be the slowest escapees, subject to relatively low levels of shock acceleration. For a Ceres-like target, even one composed entirely of ice, complete vaporization of possible ejecta is not the explanation. We can therefore consider whether fragmentation of the escaping ice, into sizes too small to be detectable, could explain the missing Ceres family. Fragmentation of ice is certainly easier than fragmentation of rock, all else being equal, although as just argued the largest just-escaping family members will be the least shocked, and the least comminuted.

While the dynamic fracture properties of ice extrapolated to geologic scale is debatable, as is the question of whether escaping ejecta are discrete fragments or bound clusters, perhaps a better place to look for evidence of icy ejecta is Europa, whose relatively young surface retains thousands of identifiable secondary craters (Bierhaus et al., 2001) from Pwyll and other large primary craters. Many of these secondaries are several km diameter, caused by ejecta fragments hundreds of meters in diameter ejected at velocities $\sim$0.1–1 km/s, demonstrating a minimum size fragment that can be abundantly created by impact into pure ice. The typical impact speed into Europa (and hence the strain rate that governs fragment size) is about an order of magnitude faster than the typical impact speed into Ceres, so it is expected that Ceres ejecta fragments would be considerably larger.

As a final note, modern studies of asteroid family formation find that fragmentation is not so relevant to the size distribution, and that most of the major family members from cratering-type family formation are gravitational agglomerations of completely damaged materials. So, while much research remains to be done in the study of family formation for asteroids of various composition, it can be safely concluded that the Ceres family did not disappear in a 'puff of smoke' upon ejection from the asteroid.

1.6. Formation elsewhere?

Another intriguing possibility exists that would allow Ceres to plausibly avoid an impact that could have created a family: if it were formed elsewhere, and later transported to the main asteroid belt.

The Nice Model and its variants (Gomes et al., 2005; Morbidelli et al., 2010; Nesvorný et al., 2013) predict a period several hundred million years after the formation of the Solar System when interactions between the giant planets led to large-scale transport of material from the outer Solar System to the inner Solar System, including the capture by Jupiter of its Trojan asteroids. It has been suggested that Ceres could have been one of the bodies formed as a TNO and transported inward (McKinnon, 2012). If this was the case, then Ceres could have avoided the period of most intense collisions in the asteroid belt, arriving after the population had shrunk to its current numbers.

The grounds for considering Ceres a transplant from the TNO region are incomplete at best. The surface composition of Ceres has been interpreted in the past as indicating ammoniated phyllosilicates (King et al., 1992), and the possible presence of NH_4^+ leads naturally to considering an outer Solar System origin. However, other interpretations for the ammonium absorption features exist (indeed, more recent interpretations assign those absorptions to brucite: Milliken and Rivkin (2009)), and mid-IR spectra of Ceres appear inconsistent with ammoniated species (Rivkin et al., 2012b).

A further serious problem remains with the above scenario: even if Ceres avoided the first several hundred million years of main belt bombardment history, we would still expect it to be a likely target for family-forming impacts in the last 3+ billion years (as noted above in Section 1.4), when most of the identified asteroid families are thought to have been created. Being such a large target, it seems likely that an identifiable family would have been produced from Ceres just as they have been from most of the other large asteroids. So we do not consider this to be a plausible explanation for the missing Ceres family.

2. Mechanisms for removing a Ceres family

2.1. Collisional and dynamical erosion

Families are subject to post-formation modification by collisional and dynamical processes (e.g., see Brož et al. (2013) for insights). If most family members were only a few kilometers in size, and the family event occurred billions of years ago, it is possible that Yarkovsky-driven mobility combined with collisional evolution could have rendered the family unobservable (Brož et al., 2013; Bottke et al., 2013). On the other hand, if the family was roughly the same size as the 1 Gy old Vesta family, or it was larger, collisional and dynamical evolution work indicates it would be hard to eliminate all traces of a Ceres family within a few billion years. Thus, much depends on the size frequency distribution of the ejected family members. The process of erasing asteroid families from antiquity warrants a careful detailed study in the near future. However, it seems likely that these processes will not be sufficient to entirely remove a Ceres family.

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. This question is similar to that addressed by Davis et al. (1998) concerning the lack of a family associated with 16 Psyche. Their simulations found that while a hypothetical Psyche family would have been ground down by a factor of 100, enough 1–10 km bodies should have survived to be detectable. O'Brien and Greenberg (2005) 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. O'Brien and Greenberg estimate maximum drift rates of order 10^{-4} AU/Myr due to the diurnal Yarkovsky effect for stony 1-km objects near 2.5 AU, with seasonal effect smaller still. 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. 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.

2.2. Dynamical scattering and reaccretion

A more nuanced possibility is that Ceres itself is responsible for dispersing its family. Carruba (2013) studied the evolution of the Hygiea family, finding that Hygiea is massive enough that it can gravitationally influence members of its family. Ceres' larger mass could be expected to be more effective in altering the orbits of close approachers, which would necessarily include any family members. However, it is not clear that Ceres could effectively "clear its neighborhood" (making it a bona fide planet, ostensibly), and it seems likely that at the least, a halo of objects identifiable as related to Ceres would remain.

Carruba et al. (2003) studied the effects of Ceres on the orbits of the nearby Gefion and Adeona families, finding that close encounters can only impart as much as ~60 m/s to the apparent ejection velocities of those family members, good for an orbital change of only a few hundredths of an AU at these solar distances. A fuller quantitative study of the effect that scattering encounters would have on a "real" Ceres family would be an important study, but is beyond the scope of this paper. We also note that the Hygiea family itself is not straightforward to interpret, as discussed further below.

Relatedly, one might consider whether Ceres could have swept up its own asteroid family after its formation. Until potential family members are scattered away from intersecting orbits, there will be some likelihood of subsequent re-collision. Low-speed collisions like those that might be expected for collisions between Ceres and putative family members would likely result in very little ejecta moving fast enough to escape, and therefore the entire process may seem to lead toward removing the family. However, there would likely be a large number of near-misses for every collision and in sum those near-misses would alter family orbits such that many former Ceres-crossers would merely become Ceres-approachers, leaving a group of halo objects (see for instance Carruba et al., 2013) that we do not see in the asteroid population. Furthermore, this argument can also be applied to Vesta as well as to other family parent bodies/largest fragments, which have clearly left a large fraction of the family unaccreted.

2.3. Sublimation of an icy family

It is also possible that rather than suffering collisional or dynamical erosion, any once-existing Ceres family experienced sublimation. This idea is not original with this work, and others have broached the idea in a qualitative sense (Li et al., 2006; Rivkin et al., 2012b; Milani et al., 2014) Ceres' shape and moment of inertia have been interpreted as indicating an ice shell above a rocky core (Thomas et al., 2005), in agreement with thermal evolution models (McCord and Sotin, 2005; Castillo-Rogez and McCord, 2010). These thermal evolution models predict the top ~10 km of Ceres would remain undifferentiated (McCord and Sotin, 2005), but the density contrast between the undifferentiated crust and the warm ice shell below would likely cause the crust to founder. 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 (Fanale and Salvail, 1989; Schorghofer, 2008).

To first order, an icy Ceres family is subject to the same surface sublimation rates as Ceres itself. Can its members have simply sublimed away? To investigate this question, we must put reasonable values to the temperature expected on such family members, the sublimation rate found at those temperatures, and how those temperatures and rates may be affected by processes like lag deposit buildup on the family members themselves. In turn, those processes are dependent upon the amount of non-ice material present, as shown below. Unless otherwise stated below, we assume a spherical, zero-obliquity body, a simple model allowing a semi-quantitative discussion of feasibility. While a full model treatment is beyond the scope of this work, the order-of-magnitude argument presented below shows that sublimation may have been a powerful force in erasing any Ceres family, and we argue that this simplified model understates the case for sublimation.

The sublimation rate is a sensitive function of temperature: at 145 K and above, a 30 km icy body would be left with only 5% of its mass after 200 My, compared to 63% at 140 K. Whether the peak temperature or average temperature is the appropriate one to consider depends on whether the ice is at the surface or buried at least one annual skin depth (~2–5 cm depth for objects at Ceres' orbital distance) beneath a lag deposit. As discussed below, it is not clear whether a lag deposit can be easily created, and so we consider the both the peak (subsolar) temperature T_{ss} and the average equatorial temperature T_{av} (Lebofsky and Spencer, 1989; Harris and Lagerros, 2002):

$$T_{ss} = \sqrt[4]{\frac{(1-A)}{\epsilon\sigma\eta}\frac{S}{\Delta^2}} \tag{2}$$

$$T_{av} = \sqrt[4]{\frac{(1-A)}{\epsilon\sigma\pi}\frac{S}{\Delta^2}} \tag{3}$$

where A is the Bond albedo, ϵ is the emissivity (taken as 0.9), S is the solar constant (at 1 AU), Δ is the solar distance, and η is the beaming parameter. We note that Eq. (3) is also used in the "Fast Rotating Model" (also called the "Isothermal Latitude Model").

The sublimation rate E into vacuum in units of mass per area and time (Schorghofer, 2008) is

$$E = p_s(T)\sqrt{\frac{m}{2\pi kT}} \tag{4}$$

where $p_s(T)$ is the equilibrium vapor pressure at temperature T, and m is the mass of a water molecule (or to generalize, the molecule of interest).

As noted, a critical factor in sublimation is the purity of the ice and amount of non-ice material present, which can have a major influence on the temperature. To estimate the likely temperatures for icy Ceres family members, we turn to the icy satellites, with well-known geometric and Bond albedos (Castillo-Rogez, 2012). Inserting the Bond albedo of Enceladus into Eqs. (2) and (3) to represent a very fresh ice surface results in a peak temperature of ~123 K and an average temperature of ~90 K, well below the temperature required for stability against sublimation over the age of the Solar System. Using the Bond albedo for Ganymede, however, 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). Intermediate between these two icy surfaces are Europa and some of the mid-sized satellites of Saturn like Tethys, Mimas, and Rhea, with Bond albedos ~0.6–0.65. That albedo results in peak temperatures near 185 K, which results in significant sublimation to sub-solar areas.

In this case we consider Ganymede to provide a more appropriate choice of albedo than Enceladus because the latter maintains its high albedo through its activity, and that activity helps maintain the higher albedos of other saturnian satellites as well (Verbiscer et al., 2007). Rabinowitz et al. (2008) notes that nearly every icy body in the Solar System with an albedo in excess of ~0.4 maintains that high albedo via known or suspected resurfacing on short timescales ($\lesssim$100 Myr), which would not be expected on a ~10-km scale object like those we consider. Indeed, rather than maintaining a high albedo, we would expect any impurities/non-ice material present to likely be susceptible to darkening via UV irradiation and proton bombardment, similar to what is seen in outer Solar System small bodies (or, depending on the nature of the non-ice material, similar to the space weathering seen on S-type asteroids).

Irradiation experiments on plausible cererean ice impurities are rare in the literature, but Nash and Fanale (1977) found significant darkening in bloedite, halite, and iron sulfate during 5-keV proton irradiation, with sample reflectances dropping by a factor of 2–4. The time to reach equivalent proton doses from solar and galactic sources in the asteroid belt ranges from ~500,000 years for the iron sulfate to ~50 My for the halite and bloedite samples (Peplowski, personal communication). Darkening would occur quickly on the timescale of interest, leading to lower albedos and higher temperatures for the surface.

Table 2 shows the average temperature at the equator of a zero-obliquity body for low-albedo (Ceres-like) and higher-albedo (Ganymede-like) surfaces at three different distances: 2.77 AU (Ceres' semi-major axis), 3.00 AU (near Interamnia and Europa's semi-major axes), and 3.15 AU (near Hygiea, Themis, and Euphrosyne) for latitudes off the equator, the temperature varies as $\cos^{1/4}$(latitude). Higher-obliquity bodies have temperatures that can widely vary over the course of the year, with temperatures that can be tens of K higher or lower depending on local season. As noted above here we maintain the simplicity of assuming zero obliquity, though including it would only strengthen our arguments: higher obliquity increases the fraction of a body that experiences subsolar temperatures, and polar areas in particular would experience long periods at high temperatures, with much greater sublimation as a result.

2.3.1. Lag deposit formation and consequences

Schorghofer (2008) studied the survivability of near-surface ice in asteroids, in the context of the "main belt comets" (MBCs). He notes the insulating effect of even a small amount of regolith, which varies as a function of porosity (ϕ), particle radius (r), and ice-free layer thickness (Δz):

$$\bar{J} = \frac{2\pi}{8+\pi}\frac{\phi}{1-\phi}\frac{1}{\tau}\sqrt{\frac{2m}{\pi kT}}p_s(T)\frac{r}{\Delta z} \tag{5}$$

where τ is the tortuosity.

With a porosity of 0.5 and 30-μm particle size, even a 1 mm regolith layer slows the sublimation rate by a factor of 100. Of course, the buildup of a lag deposit is fundamentally related to the amount of non-ice material available within the ice able to make a lag.

Speaking generally about the results from Eq. (5), a lag is produced up to the thickness at which further sublimation slows to a small fraction of the vacuum value, because of the insulating effect of the layer above mitigating temperature extremes and because a direct path for molecules is blocked. The temperature mitigation takes several centimeters at Ceres' orbital distance, and below a layer of that depth sublimation is dampened by a factor of 1000 or more. To create such a layer, however, sufficient non-ice material must be available. Models of cometary lag formation usually assume a 1:1 proportion of ice and dust.

However, after differentiation the icy mantle of Ceres likely has a much, much smaller fraction of non-ice material than typical comets, and the icy satellites are again better analogs. Zolotov (2007) modeled the oceanic chemistry of Enceladus, which is smaller than Ceres and so is a conservative point of comparison. Zolotov found Enceladus' oceanic salinity would have ranged from 2 to 20 g/kg of water, less than Earth's oceanic value of 35 g/kg. We can consider these cases as rough but plausible guides to the amount of non-ice material that could be carried in the cererean ice. These values would result in non-ice lag deposits of ~mm-cm depths for every meter of ice sublimed, although they may still be overestimates by factors of up to 100 (Castillo-Rogez, personal communication).

Even lag deposit thicknesses of millimeters can have a significant dampening effect on sublimation, as noted above. However, the size–frequency distribution of non-ice particles in the upper cererean mantle is very different that what is found on comets. Furthermore, as noted, particles smaller than a certain size will be carried along with gas outflow rather than remain to form a lag. Large, native particles are not expected to be present near Ceres' surface if it differentiated; Newton's Law predicts mm-size particles would have a terminal velocity of ~1 m/s through liquid water on Ceres, and they would reach the rocky core on the

Table 2
The temperature experienced by a body is tied to its albedo and solar distance. For the two albedos shown (Ceres-like and Ganymede-like), the average temperature at the equator is shown (assuming zero obliquity), along with the corresponding retreat rate of ice at that temperature both in vacuum and beneath a layer of 30-μm particles of 1 m depth, with other properties described in the text.

Solar distance (AU)	Geometric albedo	Avg T at equator	Vacuum retreat rate (km/My)	1-m lag retreat rate (m/My)
2.77	0.07	181	310	2.6
2.77	0.42	167	19	0.16
3.00	0.07	174	80	0.67
3.00	0.42	161	4.8	0.04
3.15	0.07	170	35	0.30
3.15	0.42	157	1.8	0.02
3.43	0.07	163	7.6	0.06
3.43	0.42	150	0.3	0.002

timescale of a day given current models of the mantle thickness. Given that interior models of Ceres suggest the ice mantle is upward of 100 km in thickness (Thomas et al., 2005), cratering impacts into Ceres would only sample the ice shell without involving the rocky core below – the giant Venenia and Rheasilvia basins on Vesta are only 12 ± 2 and 19 ± 6 km deep, respectively (Schenk et al., 2012), far short of the depth needed to breach Ceres' ice shell. Thus, we would expect Ceres family members to have very low non-ice fractions similar to the ice shell from which they are generated.

While the objects we consider are less like comets than icy satellites in terms of ice purity and non-ice fraction, we can turn to the cometary literature for insight into lag deposit development, given that the thermal and gravitational environment of an icy fragment of Ceres may be similar to that of a comet. Several workers define a critical particle size a_c at which gas drag from subliming ice balances the gravity of the comet (Rickman et al., 1990; Prialnik et al., 2004; De Sanctis et al., 2010; Jewitt, 2012). We use the formula for the largest particle that can be ejected from a cometary nucleus to determine lag deposit development on the icy objects we might expect to make up a Ceres family.

$$a_c = \frac{9\pi}{8}\frac{C_D V_{th}}{G\rho_g\rho_\beta D}\frac{dm}{dt} \tag{6}$$

Where C_D is a dimensionless drag coefficient (here set to 1, after Jewitt (2012)). We take 20 km diameter (D) as the largest object of interest, similar to the largest members of the Pallas, Vesta, Sylvia, and Nemesis families. As a relatively pure icy body ejecting low-density grains, we set the grain and body densities (ρ_g, ρ_β) to 1000 kg/m^3. We use 500 m/s as the gas speed, on the slower end of what is seen in comets at 2.5–3.5 AU (Biver et al., 2002), but roughly the speed of H_2O molecules at the relevant temperatures.

Table 3 shows the maximum liftable particle size for average temperatures at a variety of relevant conditions from a low-albedo object at Ceres' solar distance to a high-albedo object at the distance of Cybele. For hypothetical Ceres family members of 20-km diameter, this maximum liftable particle size ranges from <10 μm at higher latitudes to ∼100 μm or larger near the equator at the average temperature. As seen, the particle sizes are inversely proportional to object size, so gas outflow from a 5-km Ceres family member would be able to carry particles 4 times larger than 20 km bodies. We also reiterate that sub-solar temperatures are higher than the average temperatures by a factor of $(\pi/\eta)^{1/4}$ (Eqs. (2) and (3) above), or ∼40–60 K for the bodies we consider here and typical values of η. While these peak temperatures may only last for a short time per rotation (depending upon obliquity and season), they can potentially lift much larger particles than those listed in Table 3.

Table 3
The retreat rates in the previous table are the equivalent of mass losses. The flux of sublimed vapor leaving a body along with the body's escape speed will define how large a particle can be ejected from the surface via gas flow. The temperatures expected on low-albedo Ceres family objects are sufficient to loft ∼mm-scale particles near their equators, and even high-albedo objects should be able to eject particles of ∼100 μm or greater from their equator.

T (K)	H_2O dm/dt (kg m^{-2} s^{-1})	a_c, 20 km body
150	9×10^{-9}	1 μm
155	3×10^{-8}	4 μm
160	1×10^{-7}	10 μm
165	4×10^{-7}	50 μm
170	1×10^{-6}	0.1 mm
175	3×10^{-6}	0.4 mm
180	7×10^{-6}	1 mm

While speculative, it will be useful to also consider the appropriate particle size for material left behind from subliming ice. We take the surface of Ceres itself as representative of the sort of lag deposit under discussion. Ceres has a thermal inertia ($\leqslant$15 J m^{-2} K^{-1} s$^{-1/2}$: Spencer et al., 1989) comparable to that of the lunar regolith when the temperature dependences of thermal capacity and heat capacity are taken into account (Rivkin et al., 2012b). The lunar regolith has a typical grain size on the order of 50–100 μm, capable of being held aloft by the gas outflows discussed here.

Fig. 1 shows a_c, the largest particle ejected as a function of temperature for several different asteroid sizes, for the conditions set above (save for the 50-km case, where the body density was increased to 2). We note that a_c is a radius in the calculations and figure, while regolith particle sizes are typically thought of as diameters. Vertical lines denote the average equatorial temperatures expected at the distances of Ceres, Hygiea/Themis, Cybele, and a more general 3.0 AU distance. The positions of several large asteroids are also plotted using their asteroid numbers, including Ceres itself.

Sublimation provides a plausible mechanism for preventing lag deposit formation on members of a Ceres family. Even in the high albedo case, a 20-km body can eject 160-μm diameter grains at its equator assuming the average temperature. At ±30° and poleward latitudes, only 1–10-μm grains can be ejected, but if a lag deposit is created, it should darken (see discussion above) 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 as discussed non-zero obliquity would increase the fraction of the body experiencing sub-solar temperatures and increase the overall sublimation rate. Winter temperatures may lower the liftable particle size, but the accompanying decrease in sublimation rate with temperature means that a lag deposit will not develop in winter, either.

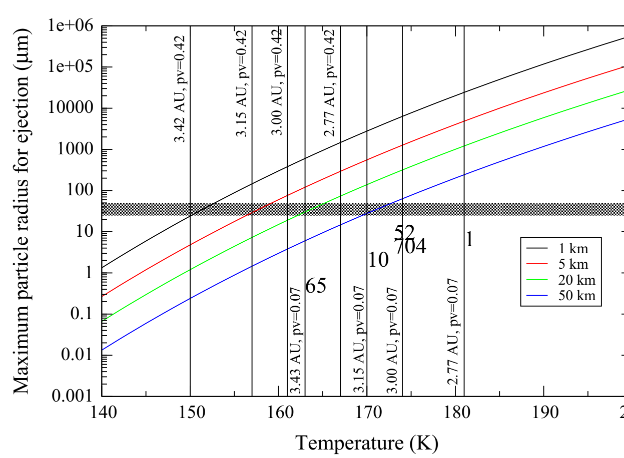

Fig. 1. As temperatures increase and/or gravity decreases, the size of particle that can be ejected from a surface by gas flow increases. The vertical lines indicate the average equatorial temperatures for objects of Ganymede's albedo (0.42) and Ceres' albedo (0.07). The stippled area indicates the mean particle size of lunar regolith, taken as an estimate of the particle size of a lag deposit. Several large asteroids are also indicated with their asteroid number. Only small particles can be ejected from their surfaces, while even relatively distant objects could theoretically eject regolith if they are small and have a low albedo.

2.3.2. Accrete a dust mantle?

For completeness, we can also make a quick estimate of whether a body could sweep up enough interplanetary dust to accrete what is functionally a lag deposit. For simplicity we take the volume (V) swept out by an object as the torus created by its cross-sectional area (A) and orbit circumference:

$$V = 2\pi a A \tag{7}$$

where a is the semi-major axis. Since particle random velocities are much faster than the few-m/s escape velocity of the body, we can ignore gravitational focusing of the dust. The material swept up in a single orbit is the volume times the mass density of cosmic dust in the asteroid belt, ρ_{belt}. Therefore the amount of mass accreted in an orbit is $V\rho_{belt}$. Assuming a density for a given grain (ρ_{grain}) allows the accreted volume to be calculated. Because the object is rotating, we assume the dust is distributed across the entire body, so the depth of material accreted is equal to the volume accreted divided by the surface area (which equals $4A$). The area appears in both numerator and denominator and cancel out, leaving the depth (Δz_{dust}) accreted per orbit as:

$$\Delta z_{dust} = \frac{(2\pi a)\rho_{belt}}{4\rho_{grain}} \tag{8}$$

The orbit period for objects near Ceres' semi-major axis is 4.6 years, so we can assume Ceres (and any Ceres family members) have completed at most billion orbits with no loss of accuracy. We estimate ρ_{belt} at $\sim 4 \times 10^{-20}$ kg/m^3 (Leinert, 1975; Willis et al., 2005), giving an accretion depth of $\sim 10^{-14}$ m per orbit and $\sim 10^{-5}$ m over Solar System history. A 10-μm layer, in the essentially-impossible case that it would remain intact, would impede sublimation by only ~10–20% compared to no layer at all, a decrease too small to maintain an object that would have otherwise disappeared via complete sublimation.

3. Open questions

While the formation and subsequent sublimation of an ice-dominated Ceres family is consistent with what we know and expect from thermodynamics, as well as being the most plausible answer to the conundrum offered by population statistics and impact mechanics, it also gives rise to a number of questions.

3.1. Should a dust band be present?

If Ceres family objects sublime away, leaving only non-ice material behind, we might expect dust bands associated with Ceres. Although dust bands are easily detectable with infrared satellites, the orbits of dust particles decay very rapidly, moving from circular orbits in the asteroid belt to 1 AU on timescales of

$$\tau_{decay} \approx 500\rho s(a^2 - 1) \tag{9}$$

where τ_{decay} is in years, a is semi-major axis in AU, ρ is density in g/cm^3, and s is particle size in μm (Wyatt and Whipple, 1950; Nesvorný et al., 2008). For non-ice dust released at Ceres' semi-major axis of 2.77 AU with a density of 2.5 g/cm^3, the decay timescale is under 10,000 years for 1 μm particles and under 10 My for 1 mm particles. In addition, once the furious dust production is finished shortly after the family-forming collision takes place, dust would be released more gradually from any subliming body, making it more difficult to detect even if somehow ongoing after billions of years.

3.2. Why do Hygiea and Themis have families when Ceres does not?

Despite previous conceptions to the contrary, there is spectral evidence that Ceres is not a body with a unique composition. Surveys in the 3-μm spectral region (see Table 1) have found other bodies, notably Hygiea (Takir et al., 2011; Rivkin et al., 2012, paper in preparation), with Ceres-like absorptions attributable to brucite and carbonates. To the extent that Ceres' surface properties and spectrum are interpreted as due to a lag deposit overlaying an ice shell, a similar interpretation and history might be applied to these other asteroids. Indeed, Castillo-Rogez and Schmidt (2010) found that the Themis family parent body, which they model as 400 km diameter, has an evolutionary pathway leading to Ceres-style differentiation, with an undifferentiated crust of varying thickness depending upon the timing of formation. These models should also be applicable to Hygiea, of a similar size to the Themis family parent body, and located very nearby in terms of solar distance.

However, Table 1 also shows that Hygiea is associated with a family. The existence of Hygiea's dynamical family is the biggest inconsistency with a subliming and disappearing Ceres family scenario, at least if Hygiea has an interior structure similar to Ceres. There are possible ways to resolve this inconsistency, but none are currently fully satisfying. We can note first that Hygiea is at 3.15 AU compared to Ceres' 2.77 AU. This difference amounts to ~10 K in surface temperature between the two. Because the critical temperature for ice sublimation is so close to the temperatures in question, a few kelvins in either direction leads to a large difference in the lifetime of ice on these two bodies and at their distances, and an icy Hygiea family may be retained much longer than a cererean equivalent.

However, Masiero et al. (2013) report an average albedo of 0.068 ± 0.022 for the Hygiea family, which should result in higher temperatures than considered above. Fig. 1 suggests that a 20-km low-albedo Hygiea family member should be able to eject ~200 μm grains. It is difficult to imagine a realistic sublimation scenario that maintains a low-albedo Hygiea family and completely destroys a Ceres family, if Ceres and Hygiea have similar compositional structures, with a relatively thin lag deposit protecting an icy mantle from the vacuum of space and with collisional family members created from impacts into that mantle.

Perhaps it is the case, then, that Hygiea and Ceres do not share the same structures. Hygiea could have retained an undifferentiated crust above an icy mantle, whether due to a colder, stiffer mantle, a lower tendency for the crust to founder due to lower gravity, a slightly later accretion time, or a combination of these factors. In the simulations of Castillo–Rogez and Schmidt, a crust of upward of 50 km can be retained with realistic starting conditions. If so, the Hygiea family could be generated from this original crust and would not be subject to sublimation. However, the spectral similarity between Ceres and Hygiea is less easily explained in this case.

The Hygiea family is not well-understood, and the identity of its largest members are debated. While Masiero et al. include 52 Europa in the family, the Nesvorny (2012) list has 159 Aemilia as its second-largest member, and Carruba (2013) has 1599 Giomus as the largest core member and 1271 Isergina as the largest halo member. Obviously, the nature of a dynamical family will be interpreted very differently if its largest member is ~400 km in size and its second-largest member is either 300 km, 125 km, or 50 km. Carruba also notes that Hygiea is near the edge of the family, with possible explanations that include formation of the family via an oblique impact, dynamical mobility of Hygiea itself relative to the family, the formation of multiple Hygiea families causing an apparent offset, or that Hygiea is an interloper in its own family.

If Hygiea is in fact an interloper in the Hygiea family, this would greatly strengthen its similarity to Ceres and perhaps remove the inconsistencies discussed above. Because of its position near the edge of its family, this conjecture is not as ad hoc a solution as it may seem. As a C-class asteroid in a region of the asteroid belt with a background population of other C-class asteroids and near other prominent C-class asteroid families, assigning family memberships is not straightforward. Nor would it be the first case where an asteroid was removed from its "own" family, as seen with Ceres itself. Many of the arguments we make here about the lack of a Ceres family can also be used to predict that Hygiea is, in fact, an interloper. More dynamical work, beyond the scope of this paper, will need to more firmly establish Hygiea's relationship with the Hygiea family.

The Themis family provides another potential challenge to explaining the missing Ceres family. Ice frost has been detected on the surface of Themis (Rivkin and Emery, 2010; Campins et al., 2010), indicating another ice-bearing parent body, perhaps like Ceres. The Themis family is one of the largest in the main belt, and there is no basis for considering 24 Themis itself an interloper. But the Themis family is generally accepted as the result of a catastrophic collision (Durda et al., 2007, for instance), as opposed to the other "cratering-type" collisions we are considering here; therefore as noted by Castillo-Rogez and Schmidt (2010), the outcome of the Themis family-forming collision may be many ice–rock mixtures of various proportions, and not pure ice fragments.

After Themis itself, at ~200 km diameter, the next largest member of the Themis family is 90 Antiope (~140 km), and then another 3 bodies at 100+ km, and yet another at ~90 km (Nesvorny, 2012). As a result, a number of the assumptions made above for Ceres family members would not necessarily hold for Themis family members overall, seeing as the family is the result of a catastrophic disruption event.

Overall, ice fractions between 15% and 60% are found for family members in the Castillo–Rogez and Schmidt models for Themis disruption, and most of the reaccumulated bodies, post-disruption, would have much higher near-surface non- ice fractions than the presumed Ceres family members we consider above (which are mostly icy, with mostly dust- to sand-sized silicate fragments). Catastrophic disruption remnants would contain larger non-ice fragments (rocks and boulders), dynamical ejecta in addition to any material dissolved or transported in water, astro-fluvially. A cratering event into an icy outer mantle leads to a far more efficient path for ice sublimation, creating sheets of exposed ice or water, transporting mostly small-sized non-ice components. So the fragments of a dirty icy mantle would lose silicates readily, while mechanical mixtures of similar sized rock and ice fragments might not. This is obviously a complicated problem in geophysical fluid mechanics, but conversely, the essential data that are required to constrain geophysical dynamics of differentiated planets, may be found in asteroids like Themis and Ceres.

An icy Themis family is overall supportive of the scenario above of a sublimated Ceres family. At least two of the "activated asteroids" or "main belt comets" are members of the Themis family, or orbit nearby (Jewitt, 2012). These show evidence of cometary activity, indicating that ice can survive for a billion years or more in km-sized planetary bodies at 3.15 AU. This is consistent with our estimates for ice when an icy core develops a lag protection of non-ice materials.

Table 1 includes the "3-μm type" of the large C-complex and X-complex asteroids. The terminology of Rivkin et al. (2012a) and Takir and Emery (2012) is used. The uncontroversial Sharp/Pallas-type asteroids all have families. The asteroid 704 Interamnia is classified as Sharp by Takir and Emery, but observations at different apparitions shows a mix of Ceres- and Pallas-type behavior (Fig. 2, Rivkin et al., in preparation). 65 Cybele and 52 Europa both lack families and are classified as non-Sharp/Pallas types, though details in the two classification schemes vary. The same is true of 31 Euphrosyne, which does have a family. Considering the details for these bodies are out of the scope of this work, but likely will fall in the range of those already discussed above.

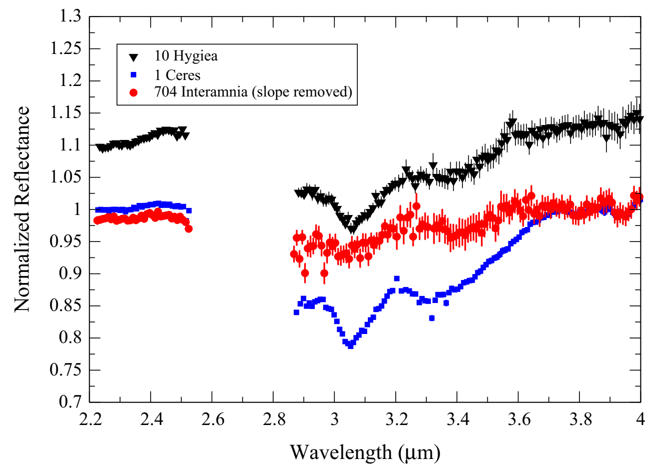

Fig. 2. Ceres and Hygiea have very similar spectra, in particular in the 3-μm spectral region. As a result, we expect a similar composition on both of their surfaces, including brucite and carbonates. To the extent that Ceres' surface composition is a consequence of its history and interior structure we expect Hygiea to also have had a similar history and structure, with an icy shell over a rocky core. Interamnia also shows similar spectral features after removal of a spectral slope, though the absorption bands are muted compared to Ceres and Hygiea. The error bars for Ceres are smaller than the data points, though the finest-scale structure near 3.3 μm is most likely due to incomplete atmospheric removal.

4. Future work

Can we ever know if Ceres once had a family? The preceding calculations and arguments suggest that any remnants of a past Ceres family, if derived from a cratering event into a differentiated icy outer shell tens of km thick, might have been completely erased. Sublimation of the ice would carry with it the non-ice solid particulates until nothing remained. If so, Ceres might have been formed and evolved in the main belt, subject to the same bombardment as Vesta and Themis and the rest, producing fragments of comparable sizes and numbers that disappeared. Enhanced collisional grinding of icy bodies might have further accelerated their comminution and loss.

Future evidence from spacecraft and telescopes will strengthen or weaken this argument for a sublimated (or otherwise missing) Ceres family, in various ways. Much of this evidence will come from the upcoming Dawn encounter with Ceres in 2015. The distribution of large craters and basins will directly constrain the amount of ejecta that may have escaped from Ceres. Furthermore, constraints on the ice fraction in Ceres' subsurface, to depths of tens of km, will be constrained by analyzing the states of those craters. Bland (2013) notes that the warm ice anticipated for Ceres would lead to rapid degradation over most of Ceres' surface, leaving palimpsests where basins once stood (Schenk et al., 2004). If viscosity (e.g., dust–ice composition and temperature) can be reliably assumed on the basis of such models, this could lead to estimates of crater/basin age, and consequently to rates of sublimation and degradation (Moore et al., 1999).

Gravity science results will directly establish the mass distribution within Ceres' global interior, leading perhaps to reliable estimates for the extent of any icy mantle. Although gravity measurements are expected to be similar in fidelity to those at Vesta (Konopliv et al., 2012), the presence and depth of a strongly differentiated ice shell and associated sublayers would be expected to present strong density contrasts that might be well resolved, especially during the course of dozens of low-altitude mapping orbits.

Studies of other large asteroids will also provide potential constraints to the Ceres family. The asteroid 704 Interamnia is a very poorly-studied object, and is the next-largest asteroid after Ceres to lack a dynamical family, assuming Hygiea is not an interloper in its own family. Interamnia orbits between Ceres and Hygiea, but is significantly smaller than either, with a diameter of ~312 km (Masiero et al., 2011). Knowledge about Interamnia's interior structure would be useful for more straightforward interpretations of its lack of a dynamical family in the context of Ceres' similar lack. The same is true of 52 Europa, the other large main-belt asteroid without a family. We can perhaps hope for future flyby missions of these important objects, to obtain more precise bulk densities and surface compositions and evidence of a family producing mega-cratering record.

Further work on the Hygiea and Themis families will also help us understand Ceres. Obtaining spectra of the Hygiea family to determine whether or not their 3-μm spectra are like those of Hygiea, should establish whether they came from the materials present on Hygiea's surface, deeper inside, or from unrelated objects. Additional dynamical and spectroscopic work to determine whether Hygiea itself is a member or interloper in its family will have an important influence on how Ceres' missing family is interpreted.

5. Conclusions

We have considered here the question of why Ceres does not have a dynamical family. Given its size and position in the asteroid belt, Ceres has almost certainly suffered impacts of the size that have created cratering-type families on other large bodies. We find it highly probable that a Ceres-like target body would produce a comparable family of escaping fragment asteroids. Given the persistence of these other cratering-type asteroid families, we find it unlikely that a Ceres family would be eroded to extinction, into bodies no larger than a few km, by collisional processes alone. As far as Yarkovsky-driven dispersal of a Ceres family, while optimal conditions might deliver km-scale members of a Ceres family outward to the nearest resonance on 500 My timescales via the diurnal effect, the competing inward drift due to the seasonal effect, a realistic distribution of obliquities, and the expected presence of larger family members all argue against this process being able to remove the large fraction of objects necessary to match the non-observation of a Ceres family.

The more likely scenario, in light of our semi-quantitative investigations described above, is that a family-forming impact into Ceres would have excavated material from an icy mantle. An icy family in the middle of the asteroid belt would have suffered significant sublimation, with gas flow sufficient to prevent the formation of a lag deposit, whether at low latitudes of low-obliquity bodies, or over more widespread areas of high-obliquity bodies. At cooler latitudes, radiation darkening of any lag deposit would likely raise the temperature to the point that outbursts could occur and reestablish sublimation. While the interior structure required for Ceres to make such an icy family is fairly well established thanks to observational and modeling work, it is not universally accepted (Zolotov, 2009). Our finding serves as an independent argument in its favor.

The continued existence of the Hygiea and Themis asteroid families requires explanation in light of this scenario, especially given the spectral similarity between Hygiea and Ceres. Several possible explanations exist for Hygiea, including that it is an interloper in its own family. These explanations require more thorough investigation. As for Themis, the nature of its family as a leftover of catastrophic disruption, rather than mega-cratering, makes its applicability to Ceres not straightforward since its family would be expected to be composed primarily of interior materials rather than only an ice mantle.

While direct evidence of a now-disappeared Ceres family is a difficult goal, indirect evidence of its origin and composition may be present. This evidence may include large, relaxed basins expected to be discovered on Ceres by Dawn, and confirmation of near-surface ice; better information for the interior structure of other large asteroids; and determination of more precise bounds for the Hygiea family and other low-albedo families.

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