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Are There Large, Never-Lithified Asteroids?

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1. Introduction and Motivation

It is well-known that the compositional distribution of meteorites collected on Earth imperfectly represents the distribution of parent body compositions in space. We expect the Earth's atmosphere to screen out weaker materials, and the Hayabusa-2 and OSIRIS-REx missions are motivated in part by the prospect of sampling material that is rare or absent in the meteorites. But in addition to the atmospheric filter is there a filter that prevents meteorite parent bodies from forming in the first place?

Rivkin and DeMeo [1] found that NEO delivery models lead to an overestimate of the number of C-complex asteroids in the near-Earth population compared to observational estimates by a factor of ~3 [2-3]. Because these estimates only involve objects in space, this discrepancy should be independent of any atmospheric effects or meteorite collection biases. There are a few possible reasons for this discrepancy, ranging from a hypothetical observational bias against discovering C-complex NEOs that has not been accounted for in debiased estimates to a bias against delivering C-complex objects from the main belt.

2. The Hydrated Mineralogy of C-Complex Asteroids

The C-complex asteroids have three major groupings based on reflectance spectra in the 3-μm region [4-5], named for type objects: Ceres types, (NH_4^+-bearing clays and carbonates); Themis types, (ice-frosted silicates and organic)s; and Pallas types, (phyllosilicates and including CM-like materials).

Only the Pallas-type absorption bands are seen in laboratory meteorite spectra, even though few of the largest C-complex asteroids have Pallas-type spectra. While plausible or well-established meteorite analogs exist for the largest medium/high-albedo main-belt asteroids, only 3 of the 12 largest low-albedo asteroids appear to be represented in the meteorite collection based on hydrated mineralogy. Similarly, several of these large low-albedo objects (but not all of them) lack a dynamical family and some low-albedo asteroid classes do not give rise to collisional families at the same rate that other asteroid classes do. There have been suggested solutions to the lack of meteorites from Ceres and, by extension, from other Ceres-type objects based on their posited internal structures [6]. Can the lack of meteorites from Themis-type objects also be explained based on physical properties?

3. Lithification of Asteroids

At this point we revisit a question first asked by Consolmagno and Britt [7]: Why do meteorites exist in the first place? Few processes can lithify asteroidal material, some of which only acted early in solar system history and some of which only operate in particular circumstances. Pressure-induced lithification requires pressures only reached (perhaps) at the very center of the very largest asteroids [8]. This is not suitable for lithification throughout the volumes of asteroids [9]. Geological processes like thermal metamorphism, aqueous alteration, and melting can lithify material, and evidence for these processes is exceedingly common in the meteorite collection [10-11]. Impact shock can lithify material, but is relatively short-range and limited to relatively shallow depths in unconsolidated material [12].

4. Are Never-Lithified Asteroids A Possible Answer?

Current asteroid formation models suggest 100-km-scale objects were constructed in the nebula from aggregation of cm-scale pieces without moving through intervening phases at smaller sizes [13]. The results of Bland et al. [14] are consistent with that finding, as their models of aqueous alteration in large carbonaceous chondrite parent bodies are described as "convecting mudballs" rather than having water altering already-lithified material.

We can ask whether lithification is an inevitable process in large asteroids. If a late-forming, ^{26}Al-poor object did not reach the melting temperature of accreted ice (or to cause thermal metamorphism if anhydrous), it may remain unlithified to this day save for any impact-lithified material. Such objects, if mixtures of ice and anhydrous silicates like what is postulated for carbonaceous chondrite precursors [11,14], will slowly sublime internal ice down to some subsurface depth based on physical properties. [15]. The lack of a widespread lithification process may leave such an object without material large or strong enough to survive the journey from the original parent body surface to near-Earth space.

If these objects exist, they may have properties consistent with the Themis-types discussed above. They are common in the outer asteroid belt, suggesting their absence from the meteorite collection is more than simply chance. This scenario is also consistent with the proposal of Vernazza et al. that IDPs are from large C-complex asteroids [19]: while impacts into unlithified objects may not eject blocks that can survive the journey to Earth, they may still generate dust that can make the journey.

5. Caveats:

While this qualitative scenario may be superficially appealing, much work remains to establish its quantitative suitability and there admittedly are some possible issues even on a qualitative level.

First is the role of shock lithification. Given the ubiquity of impacts on asteroid surfaces, the question of how much of an object's volume may be lithified by impact shock is a critical one. Second is the interpretation of asteroid collisional families in this scenario. Several Themis-type asteroids, notably Themis itself, have collisional families. This issue may be related to the previous one—it is not obvious whether the ejecta in large impacts could be largely comprised of material lithified in earlier, smaller impacts. Third, but likely not last, because the motivation for this work in part rests on the discrepancy between the fraction of C-complex NEOs we observe and the fraction we expect based on NEO delivery, we need to better understand the role of observational biases.

Confounding this entire analysis is the potential difficulty of discriminating objects that are anhydrous because they never experienced aqueous alteration (and thus are potentially unlithified) from those that had hydrated minerals destroyed through later heating/metamorphism (and thus almost certainly would be lithified). Furthermore, measurements of Themis in the mid-IR have been interpreted as indicating phyllosilicates are present [20], and we must better understand how the mid-IR and near-IR measurements can be mutually understood.

6. Conclusions, of sorts:

There are relatively few processes that can lithify material early in solar system history. Given that asteroids are thought to have formed 100-km-scale objects directly from cm-scale objects, it seems possible that some bodies in the current asteroid belt may have escaped all of those lithification processes. If gravitational aggregates of cm-size particles are unable to generate physically strong impact ejecta, then objects that are unlithified may be rare or absent from the NEO and meteorite populations. Outer-belt, low-albedo asteroids are potential candidates for such unlithified objects, as there are fewer of them in the NEO population than expected from delivery models and the hydrated minerals spectrally seen on their surfaces are absent from meteorites. Much work needs to be done to investigate whether unlithified objects can exist and whether this qualitative scenario holds up under more quantitative scrutiny. However, that additional work should lead to predictions about the nature of cometary and asteroidal surfaces that can be tested by past and ongoing missions.

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