Why We Should Study the Themis Asteroid Family in the 2023–2032 Decade

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Executive summary

The last decade of icy asteroid science has made it clear that understanding the origin and interior evolution of these bodies is fundamental for understanding the history of organics and ices in the solar system, as well as cross-cutting themes like Ocean Worlds. Observations and modeling have suggested that 24 Themis is the core of an icy asteroid, and the Themis family likely represents the fragments of an icy protoplanet broken apart by Nature's rock hammer.

In this white paper, we identify key questions in planetary science, earth science, and astrobiology, that would be addressed by further study of the interior evolution of icy asteroids such as 24 Themis. We present possible measurements and potential future research focused on the Themis family in the next decade. While much can still be done telescopically and in the laboratory, a spacecraft mission would be necessary to make key measurements that address origin and ice-rock fractionation science objectives for 24 Themis and family members.

We recommend the upcoming Planetary Science Decadal Survey identify 24 Themis and its family members as prime targets for further study and suggest both telescopic and especially spacecraft campaigns be used to explore these bodies in the next decade.

1. Science background

At the time of the last planetary science decadal survey, work was underway characterizing objects in the asteroid belt that have asteroid-like orbits but exhibit comet-like activity, known as active asteroids or Main Belt Comets (MBCs) [e.g., 1, 2, 3]. This has proved to be only the beginning in characterizing the role that icy asteroids play in the solar system. Studying the icy asteroid population addresses important questions about the migration of icy material to the inner solar system, the location of the snow line early in solar system history, and potential primordial sources of terrestrial water. However, while *Vision and Voyages* did mention MBCs, it did not explicitly include recommendations for active asteroid or MBC science.

Icy objects in the outer asteroid belt are key not only in understanding how water ice was distributed early in the solar system, but also how icy small bodies have migrated and evolved. Ceres' substantial water ice fraction (~25 wt.%), and surficial ammonium and carbon [e.g., 4, 5] suggests that it may have migrated to its current location. Evidence for surficial water ice and organics on Themis family bodies [e.g., 6, 7, 8] may support the hypothesis the Themis family could be the source of some material on Jupiter Family Comet (JFC) orbits [9]. Moreover, the Themis family parent body's likely size similarity to some Neptunian (e.g., Proteus) and Uranian (e.g., Puck) satellites make it a potential analog for icy satellites.

The Themis family provides an accessible cross-section of the interior of an icy asteroid, with 24 Themis as the likely core. The Themis family parent body was a possibly differentiated icy asteroid ~400 km in diameter (Fig. 1), which was catastrophically disrupted by a large impact [e.g., 10] about 1.0–2.5 Gya, with the smaller Beagle and 288P subfamilies forming within the past ~10 Mya [11–13]. Present day observations of fragments of the Themis parent body (e.g., the Themis family) suggest that they are largely C type asteroids, rich in ice and organic compounds [6, 7]. Recent work suggests ammoniated salts could also contribute to a 3- μ m surface feature [14], but this still suggests the Themis parent body could have migrated like Ceres. While there are many volatile-rich objects in the inner solar system (e.g., Ceres, the target of Dawn; and Jupiter Trojans, the target of the Lucy mission), the Themis family is an important keystone for understanding how icy asteroid interiors evolve.

Currently, the Themis family contains over 4,000 asteroids (Fig. 2) that show a variety of surface compositions and sublimation-driven activity [e.g., 15, 16]. Significant ice-rock

fractionation (e.g., non-lithic differentiation) of the Themis parent body could have produced daughter bodies with a range of compositions [17]. 24 Themis and the Themis family make for appealing targets for further study also as their low inclination (e.g., 24 Themis, 0.76°) makes them more accessible to spacecraft.

Water ice and organics have been detected on the surface of 24 Themis [6, 7], yet no sublimation-driven activity has been observed [e.g., 18]. This may be in part due the observational difficulty of searching for weak water vapor production at 24 Themis' position in the asteroid belt ($\sim 2.7\text{--}3.5$ AU) around such a bright object, in addition to 24 Themis' much larger mass (and therefore escape velocity) compared to MBCs. Therefore, determining the degree to which 24 Themis is outgassing, if at all, is essential to compare 24 Themis to more active daughter bodies and to determine if this difference is due to surface and subsurface water-ice abundance.

Figure 1. The Themis parent body, if differentiated as postulated in [17] before the family-forming impact, provides a rare glimpse inside an ice-rock fractionated asteroid. Figure from [19].

Figure 2. The large number of Themis family objects make them an attractive mission target. Histogram of asteroids from the IAU Minor Planet Center catalog binned by semi-major axis (gray). Dashed gray lines are asteroid/Jupiter resonances. Themis family members (black) from the PDS archive of [20]. B and C are MBCs.

The MBC population includes multiple Themis family asteroids, like 133P/Elst-Pizarro, 176P/LINEAR, and 288P/(300163) 2006 VW₁₃₉ [e.g., 1, 21], with recent work suggesting that there could be Themis family objects evolving onto JFC-like orbits in the present day [9]. All Themis family bodies could be currently losing volatiles to some degree through sublimation. One explanation for activity observed in Themis family MBCs and not at 24 Themis itself is that the icy and rocky components of the parent body separated before the family-forming impact. Alternatively, 24 Themis could contain significant ice in its deep interior, but has had its near-surface ice depleted over time. MBCs therefore would have “fresher”, more ice-rich surfaces due to more recent disruptions [21]. To test these hypothesis, outgassing rates could be determined and directly compared for several daughter bodies, including those from young sub-families. Differences in sublimation rate could be due to bulk composition or surface age, and thus assess the hypothesis that the Themis parent body underwent significant ice-rock fractionation.

In light of the major developments in icy asteroid science since the last decadal survey, especially with results from the recently completed Dawn mission and the confirmation of other

ice-rich asteroids such as 10 Hygiea [22], further study of icy asteroids is timely and important. Study of the Themis family would address the science question:

What is the source, evolution, and volatile fate of icy bodies in the asteroid belt?

2. Open science questions in planetary science addressed by Themis family studies

Further study of the Themis family is relevant the following key science questions:

From where did water and organics in the asteroid belt originate?

- *What types of organics are on the surface of 24 Themis and daughter bodies? How do they compare to what is seen on Ceres, in the C chondrites, and (eventually) in returned samples from Ryugu and Bennu? Are they diagnostic of a colder or warmer accretional environment for the Themis family parent body compared to the family's current orbit?*
- *What is the D/H ratio of water in 24 Themis and in MBC daughter bodies? Is the D/H ratio consistent with terrestrial water (e.g., could the small bodies reservoir that the Themis family parent body derived from have provided significant water to the Earth)? If not, is this D/H ratio consistent with other solar system objects? Which ones?*
- *What do oxygen isotopes from Themis family members tell us about the parent body's origin and relationship with the Earth? How do oxygen isotopes in Themis family water compare to fluid inclusions in ordinary chondrites, or to heavy water at comet 67P and hypothesized in carbonaceous chondrites? Is this consistent with D/H results?*
- *How much exogenic contamination contributed to the surface chemistry of 24 Themis and daughter bodies?*

How have water and organics in the asteroid belt evolved over time?

- *To what extent had ice-rock fractionation occurred within the Themis family parent body? How does the composition vary between the Themis family members? Could water ice identified on 24 Themis and in daughter bodies have originally been from a primordial subsurface ocean or from a well-mixed rocky and icy interior?*
- *Are 24 Themis and non-MBC daughter bodies undergoing detectable outgassing in the present day? If so, what is the outgassing rate and what is the implication for volatile loss over time? If not, is this because of an initially low water-ice abundance, or some other process e.g., thermal and impact depletion over time? Do the differences in outgassing rates correspond to the target object's surface age?*

How are water ice and organics distributed in the asteroid belt today?

- *How has modification of the surface via impact cratering and mass-wasting re-exposed organics or water ice from the interior?*
- *Has exogenic contamination altered the surface composition of the Themis family?*
- *How reliable is observed, active outgassing as a marker for ice-rich asteroid targets? Are non-detections driven by observational detection limits or by fundamental differences in outgassing mechanisms between larger icy bodies (e.g., 24 Themis, Ceres) and smaller ones (e.g., 133P/Elst-Pizarro)?*
- *Is there evidence that Themis family members could have delivered a significant amount of water ice and organics to the Earth?*

3. Relevance to NASA goals and other fields of interest to the Decadal Survey

The three core questions we have identified that further study of the Themis family would address are also relevant to broader NASA goals as outlined by the NASA 2014 Science Plan for

the Planetary Science Division (PSD) (Table 1) as well as other areas of relevance to decadal survey themes. Those broader themes are:

Planetary Science: Themis asteroid family and icy asteroid studies in general would address the questions: Where are the current water reservoirs in the solar system and how did their water budgets evolve with time? How do icy asteroids compare to other icy bodies, like icy moons and comets? How common is ice-rock fractionation in icy asteroids? Answering these questions would place in context the role that ice-rich small bodies have played in the inner solar system.

Astrobiology: What is the current distribution of organics and water in the solar system, and how do they mix to form chemically favorable environments for life? Based on our current understanding of 24 Themis and the Themis asteroid family, as well as other icy asteroids and Ceres, it appears that this type of small body carries organics and water ice. Liquid water in the interior of these objects, if a common feature of large icy asteroids, could provide an environment that modifies key chemical building blocks of life.

Terrestrial science/biology: What is the source of terrestrial water, and how was it delivered to the inner solar system? Icy asteroids may represent a reservoir of water and organics that was scattered into the inner solar system, especially if icy asteroids are more widely spread than previously detected. Whether asteroidal water has the same isotopic fingerprints as the Earth's water is still unknown. Identifying whether icy asteroid water is an isotopic match for terrestrial water would be a key result in understanding Earth's early environment.

4. Approaches to Icy Asteroid Science and Exploration

There are multiple ways of making the measurements needed to answer the core questions identified in Sections 2 and 3. *However, the only way to make all the measurements necessary to achieve the science objectives in Table 1 is with a spacecraft mission.* We address what can be achieved as a precursor to a spacecraft mission via observational campaigns and laboratory and instrument science, and justify the science need for a spacecraft mission. Finally, we present preliminary estimates on what could be achieved on a Discovery versus a New Frontiers budget.

Observations from James Webb Space Telescope (JWST) and ground based telescopes: JWST will be a valuable new resource for Themis family studies in the next decade. The 3- μm wavelength feature that is of particular interest to studying surficial water ice and organics on 24 Themis (Science Objective #4, e.g., [6, 7]) falls within the 1–5 μm wavelength range of the NIRSpec instrument ($R \sim 100, 1000$, or 2700 depending on mode) [e.g., 23]. The last two NIRSpec resolution modes could be binned to $R \sim 300$, comparable to current IRTF observations. Other key compounds that may play a major role in icy asteroid surface chemistry, based on results from the Dawn mission, also have absorptions within this range. For example, carbonates have an absorption feature at $\sim 3.95 \mu\text{m}$, ammoniated clays at $\sim 3.1 \mu\text{m}$, and aliphatic hydrocarbons at $\sim 3.4 \mu\text{m}$. Improving the spectral resolution over the surface of 24 Themis would address Science Objective #5 (Table 1), as well as extending total observation time of 24 Themis.

In general, more observations of 24 Themis, with JWST or other Earth-based assets (i.e., 8 m- to 30 m-class telescopes), would be useful in characterizing its outgassing activity which could be linked to its surface water detection. While recent searches for an exosphere at 24 Themis have yielded non-detections [e.g., 24], dust tails have been identified at its MBC family members [e.g., 1, 2, 3] hinting that similar activity may occur below the detection limit on the parent body. Though 24 Themis does not exhibit detectable sublimation-driven dust emission, this was also the case at Ceres, a known icy asteroid with numerous, non-polar water ice patches [25] which had exospheric water detected directly with the Herschel Space Observatory [26]. Currently, the inferred telescopic upper-limit of water vapor production at 24 Themis is $\sim 4.5 \times 10^{27} \text{ mol s}^{-1}$ [24].

Therefore, additional telescopic observations could help determine if 24 Themis is outgassing at a rate consistent with the detection of water ice on its surface (Science Objective #3), especially in the next decade as the sensitivity of ground-based telescopic instruments improves.

Table 1. Example science tracing from high-level NASA Planetary Science Division (PSD) goals to possible science objectives in studying 24 Themis and family.

NASA Science Plan	Science Goal	Key Questions	Science Objective
Explore and observe the objects in the solar system to understand how they form and evolve (#1/5 from 2014 NASA PSD)	From where did water and organics in the asteroid belt originate?	Did evolved, ice-rich protoplanets form in situ, migrate from the outer to inner solar system, or accrete components that migrated from the outer solar system?	1. Determine where the Themis parent body and/or its components formed: in its current orbit in the Main Belt or in the outer solar system.
Advance the understanding of how the chemical and physical processes in our solar system operate, interact, and evolve (#2/5 from 2014 NASA PSD)	How have water and organics in the asteroid belt been processed over time?	Via what processes did the interiors of ice-rich protoplanets evolve: did they undergo significant ice-rock fractionation or form a mudball?	2. Determine whether the Themis parent body was differentiated and, if so, to what extent, via identifying and interpreting compositional differences between Themis and outgassing daughter bodies
		What processes occur on the surfaces of Themis family members, and how do they compare to those on the surfaces of comets?	3. Discriminate between mechanisms for outgassing on Themis in comparison to active daughter bodies, and distinguish if/how they differ from comets.
		Where were water and organics distributed throughout the Themis parent body?	4. Determine if 24 Themis' surficial composition is representative of composition at m- and km-scale depths.
Explore and find locations where life could have existed or could exist today (#3/5 from 2014 NASA PSD)	How are water and organics distributed in the asteroid belt today?	Is the 3- μ m absorption on Themis' surface from surficial water ice?	5. Distinguish between water ice or hydrated minerals as the compositional component(s) responsible for the 3- μ m absorption on 24 Themis' surface.
		Does exogenic organic contamination play a large role on the surfaces of asteroids?	6. Determine whether exogenic organic contamination is present in the regolith of 24 Themis and additional daughter bodies, in comparison to the composition at m and km-scale depths.

Laboratory, modeling, and instrument development work: Refinements in the internal modeling of icy asteroid evolution can and have been made based on results from the Dawn mission. Revisiting previous models of Themis parent body interior evolution [17] should be possible in the next decade, including how the family's dynamical evolution could have partitioned daughter bodies with different compositions. Additional laboratory analog studies could shed light on processes that initiate sublimation outbursts, and quantify thermophysical parameters that current thermal models rely on to predict the surface and sub-surface temperatures of objects like Ceres and Themis family members. Furthermore, miniaturization of instruments like mass or tunable laser spectrometers would be essential to any future in situ measurements of isotopic ratios (D/H, oxygen) that would be able to address the origin of the Themis family parent body, and

possibly icy asteroids in general. All of this work would generate progress on the questions outlined in Table 1. Instrument and laboratory experiment developments are also key next steps in deriving measurement requirements for future in situ observations.

Spacecraft observations: Significant progress on the science objectives outlined in Table 1 at 24 Themis and family members requires spacecraft observations (e.g., geologic context, outgassing rate and composition, elemental abundances). Determining the origin of the Themis family parent body (Science Objective #1) and determining the degree of ice–rock fractionation that the parent body underwent (Science Objective #2), require measurements like isotopic ratios (D/H or oxygen isotopes) or determination of elemental abundances in the target body regolith (Table 2). D/H or oxygen isotopic measurements require a sample of the outgassed material for mass spectrometry or UV spectroscopic measurements from orbit (e.g., like by MAVEN’s IUVS instrument). Elemental abundances and ratios, measured from neutron spectroscopy, require a detector flown within one body radius of the object for a sufficient integration time [27].

Table 2. Measurements needed to address Science Objectives #1 and #2 from Table 1. All but the first measurement objective would require in-situ measurement techniques from a spacecraft.

Science Objective	Measurement Objective
1. Determine where the Themis parent body and/or its components formed: in its current orbit in the Main Belt or in the outer solar system.	Determine the extent of aqueously altered materials, including ammoniated phyllosilicates and other ammoniated species, that indicate low temperature alteration processes on target body surfaces
	Determine the bulk volatile vs. rocky content of each target body via density
	Determine the D/H ratio of water vapor escaping from the target surface
	Determine the oxygen isotope ratios of water escaping from the target surface
2. Determine whether the Themis parent body underwent ice/rock fractionation and, if so, to what extent	Determine the elemental abundances of H, C, Fe, and the ratios of Fe/Mg, Mg/Si & Fe/Si in the upper ~1 m of the surface at 24 Themis and at least one additional daughter body
	Measure the moment of inertia, gravity field, and bulk density of each target body
	Measure topography/relief and global shape of each target body

In addition to these key measurements that are best done in the vicinity of the target of interest, another key element of in situ observation is giving context to the measurements collected. Resolving the composition over the surface from IR spectroscopy and linking data to geologic units or impact craters would address Science Objective #5, where the components contributing to the 3- μ m feature would be spatially resolved by geologic unit. Also, results from Vesta and Ceres indicate that exogenic contamination plays a key role in asteroid surface chemistry [e.g., 28, 29]. Spatially resolved IR spectroscopy would also help address Science Objective #6, as differences in the elemental results from ~1 m depth from neutron spectroscopy and near-surface from IR spectroscopy could be used to quantify near-surface exogenic contamination. These additional observations bring 24 Themis and additional daughter body targets into the realm of the geologic world rather than disks of light.

In total, in situ measurements of key parameters from a spacecraft mission would address all of the science objectives in Table 1. However, some instrumentation needed to make these measurements is heavy, costly, and/or require high power, like a mass spectrometer or radar. Low cost/power/mass versions of these instruments are key to develop in the next decade. Some measurements could be made as observations of opportunity for any Themis family member on

any class of NASA planetary science mission that leaves the inner solar system. The Themis family's low inclination and eccentricity make many of these objects relatively accessible for spacecraft flybys. Spacecraft observations of opportunity like this should be used whenever possible. The Vera C. Rubin Observatory's Legacy Survey of Space and Time (LSST) should discover many more Themis family asteroids in the next decade [30], which should greatly increase the likelihood of finding suitable targets for such efforts.

However, a dedicated mission would provide a comprehensive portrait of 24 Themis and daughter bodies with directly comparable data sets needed for the highest fidelity science. Preliminary work done by aerospace engineering graduate students at the University of Colorado, Boulder, suggests a dedicated 24 Themis mission would be possible on a Discovery budget with an instrument suite similar to Dawn's (visible camera, IR spectrometer, gamma ray and neutron spectrometer) with the addition of a UV spectrometer and/or radiometer, while a cost cap exceeding Discovery would allow for the inclusion of a mass spectrometer and/or radar. Other additions to increase science return from alternative mission concept of operations (e.g., multiple spacecraft) or enhancements to the core suite instruments would require further study. A detailed trade study for a New Frontiers mission is the next step in determining the science trade between a Discovery and New Frontiers class mission.

While a detailed study between science achievable by a Discovery vs. New Frontiers class mission remains to be done, the measurements needed to answer the science questions in Table 1 require in situ observations, and by extension, a spacecraft mission.

The observations that would be possible from a dedicated Themis family mission is an unprecedented chance to peer into the interior and core of an icy asteroid. Such insight is critical for consideration for small bodies science in the next decade.

5. References

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