Astrobiology Research Priorities for Primitive Asteroids

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1. Primitive asteroids and the formation and evolution of the Solar System

Asteroids are planetesimals that largely orbit between Mars and Jupiter. Many asteroids are primitive, having escaped the high-temperature melting and differentiation that shaped the larger evolved asteroids and the terrestrial planets. The chemical and physical nature, distribution, formation, and evolution of primitive asteroids are fundamental to understanding Solar System evolution and planet formation. They offer a unique record of the complex chemical and physical evolution that occurred in the early solar nebula. The asteroid belt also preserves a unique record of collisions, breakup and cratering over the past 4.5 billion years. Detailed modeling of Solar System evolution suggests that planetary migration of Jupiter and Saturn produced sweeping resonances through the main asteroid belt and dislodged most of the asteroids. The resulting liberated asteroids were likely responsible for the impact cataclysms that occurred on all terrestrial planets and satellites around 4 billion years ago.

Understanding the origin of organic compounds in early Solar System materials is central to astrobiology. Individual asteroids are "astrobiological time capsules" that preserve a record of the evolution of volatiles and organics starting in the interstellar medium, through the birth and early evolution of the Solar System, to present-day space weathering at asteroid surfaces. Meteorites are invaluable for asteroid science and provide samples that can be subjected to detailed laboratory analyses (Lauretta and McSween 2006). Thus, studies of asteroids and meteorites are important for developing a comprehensive model of evolution of the Solar System. Furthermore, understanding of these objects is central to Goal 2 of the Astrobiology Roadmap—"Determine any past or present habitable environments, prebiotic chemistry, and signs of life elsewhere in our Solar System. Determine the history of any environments having liquid water, chemical ingredients, and energy sources that might have sustained living systems. Explore crustal materials and planetary atmospheres for any evidence of past and/or present life."

1.1 Presolar Processes

Primitive asteroids record a history of late-stage stellar evolution, the interstellar medium, the solar nebula, and Solar-System evolution. The most ancient history is recorded in small interstellar organic compounds and mineral grains, which have been isolated and studied from primitive meteorites. Each grain of stardust records its history of condensation in stellar atmospheres or supernova outflows, grain-surface reactions in the interstellar medium, and thermal processing in the early Solar System (Meyer and Zinner, 2006). These pre-solar grains are intimately embedded in diverse materials of nebular origin. Their abundances are highly variable among different types of primitive material, with the highest abundances reaching ~0.1 wt%. They survived destruction during Solar-System processing and retain memory of the astrophysical setting of their formation. These observations lead to the following key questions:

- What was the diversity of presolar material that formed the original Solar System solids?
- What processes in the solar nebula acted to alter presolar material?
- How did the presolar grains that are preserved in primitive asteroids survive the violent, early epochs of Solar System formation?
- Which asteroids contain the highest abundances of presolar material?

1.2 Volatile Condensation in the Solar Nebula

The CI chondrites are samples of some of the most volatile-rich small bodies in the Solar System. They are generally regarded as being representative of the bulk elemental composition of the Solar System, with the exception of the highly volatile elements hydrogen, carbon, nitrogen, oxygen, and the noble gases (Lodders, 2003). The reflectance spectra of the CI meteorites do not match any known asteroid type. Some have suggested that the parent body of the CI meteorites was an extinct comet (e.g., Ehrenfreund *et al*. 2001). Only seven members of this extraordinarily important meteorite group have been recovered, with a total mass of ~15.5 kg. Almost 90% of this material is represented by the Orgueil meteorite, which fell in 1864 in the Midi-Pyrenees, France. Relative to CI chondrites, all other groups of meteorites, as well as bulk terrestrial planets, are depleted in volatile elements. These observations suggest that volatility controlled fractionation played a major role in establishing the bulk compositions of most bodies in the early Solar System. Future work in this area should address these key questions:

- Where are the parent-bodies of the CI chondrites?
- Where did the CI-chondrite parent asteroids originally accrete?
- What were the fractions of icy, rocky, and carbonaceous material that accreted to form volatile-rich asteroids? What were the source regions of these materials?
- What processes produced the volatility trends in the bulk elemental abundances of primitive asteroids and the terrestrial planets?

1.3 Alteration Processes in Asteroid Interiors

Liquid water played a significant role in establishing the chemistry and mineralogy of primitive asteroids by modifying their primary mineralogy and texture (Brearley, 2006). This aqueous activity is responsible for the production of phyllosilicates, carbonates, oxides, soluble organic molecules, and other compounds. Only three chondrite groups in our meteorite collections have experienced intense aqueous alteration: the CI, CM, and CR chondrites. Of these the CI chondrites represent the definitive example of asteroidal aqueous alteration and have experienced the most intense aqueous alteration of any known type of extraterrestrial material. The CM (total known mass ~148 kg, 67% of which is the Murchison meteorite) and CR (total known mass ~13 kg, 30% of which is the El Djouf 001/Acfer059 pair) chondrites provide additional evidence of widespread aqueous alteration in the early Solar System. Despite showing characteristics of aqueous alteration, these chondrite groups have a broad range of textures, mineralogy, organic composition, and isotopic composition. Combined these three chondrite classes represent $<5\times10^{-5}$ % of all asteroidal material available for study. This extremely limited sample set drives us to ask the following key questions:

- What were the extents, durations, and intensities of hydrothermal alteration in asteroids?
- How representative are the CI, CM, and CR chondrites of volatile- and organic-rich primitive asteroids?
- Where are the most volatile-rich asteroids? What are they composed of?
- How well did primitive, volatile-rich asteroids survive the collisional evolution of the Solar System, compared to other more cohesive bodies?

1.4 Volatile and Organic Chemistry in the Early Solar System

Study of volatile-rich compounds and organic molecules in extraterrestrial materials are of inherent interest to the study of Solar System formation. The CI, CM, and CR carbonaceous chondrites are the most C-rich samples of the early Solar System available. The largest fraction of the organic carbon (>70% of the total) in CM chondrites is present as a complex insoluble macromolecular material (Cronin *et al*., 1987). CM chondrites also contain a complex suite of soluble organic molecules. For example, over 80 isomeric and homologous amino acid species have been identified in the Murchison meteorite (Pizzarello *et al*. 2003). The soluble organic molecules in CM chondrites seem to have formed during aqueous alteration. This process may have played an important role in the enrichment of left-handed amino acid excesses found in CI and CM meteorites that may have biased the early Earth's prebiotic organic inventory that led to the emergence of life (Cronin and Pizzarello, 1997; Glavin and Dworkin, 2009). In contrast, the organic compounds in CR chondrites are significantly different. Some of the CR chondrites contain large total abundances of amino acids, higher than in Murchison by factors up to ten, and other N-containing molecules (Martins *et al*. 2007), while oxidized species and hydrocarbons are present in far lower amounts. In contrast, the soluble materials in the more primitive unaltered CR chondrites are much simpler, with a rapid drop-off in abundance for longer chain molecules, do not exhibit large amino acid enantiomeric excesses, and may represent primordial organics from the interstellar medium. This complex chemistry leads to several key questions:

- How representative are the CI, CM, and CR chondrites of the entire carbonaceous asteroid population?
- What is the diversity of organic matter in carbonaceous asteroids?
- What are the chemical details of the formation of soluble organic molecules and insoluble macromolecular organic solids?
- What processes created, destroyed, and modified the carbonaceous matter that is now contained in primitive asteroids?
- Did the terrestrial L- enantiomer biological preference for amino acids result from the L-enantiomer bias found in extraterrestrial organic material?

1.5 Current Reservoirs of Volatile and Organic Material

The relationship of the colors and albedos of small bodies to their compositions and histories of alteration since their origin is essential information that will allow us to interpret remotely-sensed spectra of asteroids and, by extension, develop a geological map of processes occurring in the early Solar System. A major hurdle in understanding the distribution of volatile and organic material in the asteroid population is the lack of context resulting from the difficulty in linking asteroid spectral classes with specific meteorite groups. The diversity of the asteroid population is reflected in both the large variation in their spectral properties and the large compositional range of meteorites. Although the silicate mineralogy of asteroids can be inferred by spectral matching between asteroids and meteorites (e.g., Hiroi *et al*., 2001), the detailed mineralogy of most asteroids is still unknown. The possible parent asteroid associated with a meteorite class can be constrained with reflectance spectroscopy, and is helped when a dynamical mechanism can be identified to deliver meteorite samples. Success in connecting meteorites to asteroids began with the identification of Vesta as the source of the HED meteorites (Drake, 2001). However, there are several spectral classes of asteroids whose meteorite counterparts have been difficult to locate. In particular, presumed primitive carbonaceous asteroids have relatively flat and featureless spectra that are frustratingly difficult to link to specific chondrite groups.

This problem is compounded by the unknown effects of space weathering on carbonaceous material. Primitive asteroids that contain ice, organics, and silicates undergo distinct surface alteration effects (Emery and Brown, 2003). These processes include micrometeorite impact and reworking, implantation of solar wind and flare particles, radiation damage and chemical effects from solar particles and cosmic rays, and sputtering erosion and deposition. The result is a dark, flat, and featureless spectrum. These processes can be addressed by the following key questions:

- Which asteroids are the sources of the carbonaceous meteorites?
- What types of carbonaceous asteroids are not represented in our meteorite collections? How diverse is this population?
- What is its present-day distribution of organic matter in the solar system?

- What processes currently modify the surfaces of small primitive bodies and how do colors and albedos of small bodies relate to their compositions and histories of alteration by various processes since their origin?

1.6 Asteroids and the Delivery of Water and Organic Molecules to the Early Earth

Asteroids and comets are generally believed to have contributed to the terrestrial planets' inventory of volatiles and prebiotic organic matter. Spectroscopic measurements of the D/H ratios in cometary comae indicate that water ice in comets is more D-rich than the water at the surface of the Earth, constraining the amount of volatile material that could be delivered from cometary impacts. Furthermore, dynamical simulations of the formation of terrestrial planets suggest that the outer asteroid-belt was the primary source of impactors on the early Earth. The discovery of comets in the main asteroid belt strengthens the hypothesis that similar bodies may have delivered water and other volatiles to the inner Solar System (Hsieh and Jewitt 2006). Organic- and volatile-rich asteroids provide fundamental information about the source of water and prebiotic compounds for the terrestrial planets. These issues lead to these key questions:

- What is the role of asteroids in the delivery of volatiles and organics to terrestrial planets?
- Did organic matter delivered to early Earth (and other planets) by primitive asteroids trigger the formation of life or provide the materials?
- What is the survival rate and chemical modifications of organic material delivered to early Earth and other terrestrial planets?

2. High Priority Space Missions for the Exploration of Primitive Asteroids

Primitive asteroids are important targets for the next generation of spacecraft missions. Based on the key questions outlined above, carbonaceous and volatile-rich asteroids must be the primary targets of these missions. Below are three missions, listed in priority order, that are essential to further the science and exploration of primitive asteroids.

2.1 Asteroid Sample Return

An asteroid sample-return mission promises enormous scientific payoff and should be the top priority medium-class mission for small-body science. This mission concept has been extensively studied by independent, experienced teams in the U.S., Europe, and Japan and is very mature. In addition, such a mission serves as a pathfinder for a much more challenging Comet Surface Sample Return mission. All teams conclude that the highest value samples are pristine carbonaceous material from the early Solar System. Given our current technology and launch limitations, sample return from a carbonaceous near-Earth asteroid provides the highest science return with the lowest implementation risk. However, individual teams should be given latitude to select their target and provide the rationale for their choice. Though we have limited samples of carbonaceous material in the form of meteorites, the value of these samples is compromised by the lack of geologic context. An asteroid sample return mission must acquire samples with known geologic context. Finally, thorough contamination control and documentation is essential to achieving the objective of returning a pristine sample. Such a mission should have the following science objectives:

- Characterize the asteroid physical properties including the mass, shape, gravity field, rotation state, surface accelerations, and any satellites or small particles in orbit.
- Globally map the surface texture, spectral properties, and geochemistry of the target at sufficient spatial resolution to resolve geological features necessary to decipher its geologic history and provide context for returned samples.

- Characterize the regolith at the sampling site *in situ* with emphasis on the textural, mineralogical, and geochemical heterogeneity at resolution sufficient to compare the returned regolith to that existing on the asteroid surface.
- Return a sample to Earth in an amount sufficient for molecular, organic, isotopic, and mineralogical analyses and including documentation of all sources of contamination.

There has been discussion about the recovery of fragments of asteroid 2008 TC3 negating the need for asteroid sample return. This object was the first bolide to be observed prior to reaching Earth. After its detection 586 observations were performed in less than 19 hours. It entered Earth's atmosphere above northern Sudan at a velocity of 12.8 km/s. It exploded tens of kilometers above the ground. Forty-seven meteorites, named Almahata Sitta, with a total mass of 3.95 kg were recovered (Jenniskens *et al*. 2009). These meteorites are fragile and were not previously represented in meteorite collections. They are polymict ureilites, ultra-fine grained and porous achondrites with large carbonaceous grains. The combined asteroid and meteorite reflectance spectra identify the asteroid as F class. We have evaluated the likelihood of similar events in the near future. Even considering the increasing capabilities of the Catalina Sky Survey, Pan-STARRS, and LSST, these events are likely to occur on average only once every decade. It is unlikely that the resulting meteorites will land in a region where they can be recovered. Thus, there still exists a real need for the collection and return of pristine carbonaceous asteroidal material with well-documented geologic context.

2.2 Activated Asteroid/Main-belt Comet Explorer

Extremely volatile-rich asteroids have been discovered in the asteroid belt. Several members of the Themis asteroid family have been observed to display temporary comet-like activity (Hsieh and Jewitt 2006). Seasonal heating effects are only sufficient to drive sublimation on these bodies for a portion of their orbits, from the time of perihelion to halfway to aphelion. The recurrent activity of these asteroid-comet transition objects is thought to result from seasonal variations that periodically illuminate ice-rich surfaces. These ice-bearing objects are more accessible than all other comets, making them excellent targets for a spacecraft investigation. Furthermore, geochemical and dynamical constraints suggest that $<10\%$ of the Earth’s volatile budget was delivered by Kuiper-belt or Oort-cloud comets and that bodies from the outer main asteroid belt were the dominant source of primordial exogenous terrestrial organic molecules and water (Morbidelli *et al*. 2000; Gomes *et al*. 2005). Thus, investigation of an active volatile-rich asteroid from the main belt by a medium-class spacecraft mission, as opposed to a traditional comet, is more relevant to understanding the origin of terrestrial volatiles and organics. In addition, the transient nature of the activity provides an unprecedented opportunity to observe the onset and cessation of activity. Such a mission should have the following science objectives:

- Rendezvous with the target prior to the beginning of cometary activity.
- Measure the shape, mass, gravity field, and rotation state of the target.
- Characterize of the texture, spectral properties, mineralogy, and geochemistry of the target during its quiescent period.
- Observe the target through perihelion to document the onset of cometary activity.
- Determine the mechanism for cometary activity, whether due to recent impacts, fragmentation due to rapid rotation, or some other mechanism.
- Directly measure the composition of gas, dust, and organics liberated from the nucleus.
- Analyze the isotopic composition of liberated water, and test whether outer Main Belt objects were a major contributor to terrestrial water.
- Observe the target past perihelion to document the cessation of cometary activity.

2.3 Trojan Reconnaissance

The Trojan asteroids are aggregated about the L4 and L5 equilibrium points along Jupiter's orbit. These asteroids have low albedos and featureless, reddish spectra. They may have formed in the same nebular region as Jupiter and represent unmodified building blocks of the Jovian system. Alternatively, if Jupiter migrated inward after its formation, the Trojans may have been captured in their present orbits during giant planet formation and migration. Characterization of the Trojans is therefore central to understanding the formation and migration history of Jupiter and its satellites and provides a means of testing the "Nice model" (Gomes *et al*. 2005). In either case, Trojan asteroids are likely rich in organics, sampling regions of the nebula at or beyond 5 AU, and representing an unexplored frontier of the Solar System. Thus, detailed study of these objects is essential to expand our understanding of the history of volatiles and organic molecules in the early Solar System. This mission should achieve the following:

- Rendezvous with the target to permit extended observation.
- Measure the shape, mass, gravity field, and rotation state of the target.
- Characterize its texture, spectral properties, mineralogy, and geochemistry.
- Determine the relative abundances and compositions of rocky, metallic, organic, and icy material

3. Supporting Research and Facilities

3.1 Physical Characterization of Asteroids

Mission planning to primitive asteroids requires a substantial amount of *a priori* information about the target. Thus, a real need exists for extension of asteroid surveys beyond discovery to include physical characterization, with a preference for characterization of promising mission targets. Basic characterization of the composition of an asteroid is essential to plan a mission to the most scientifically intriguing objects. Orbit determination is critical to evaluate the total delta-V for a mission and ensure rendezvous. The size, density, and rotation state of potential targets are needed to plan spacecraft proximity operations. Accurately determining size requires knowing the shape and albedo. Knowledge of the asteroid environment, including the characterization of satellites, dust, and active volatilization, is important to ensure mission safety.

3.1.1 Spectroscopy

Asteroids are classified according to their taxonomic type. Spectroscopy from Earth is usually disk integrated, taking in a hemisphere at once (Asphaug 2009). It can be rotationally resolved—recorded as the asteroid spins, documenting global heterogeneity. Visible and near-IR spectroscopy is used to derive the taxonomic class and compositional information of the surface.

3.1.2 Radar Observations

Asteroid radar enables studies of surface roughness and albedo. Radar provides extraordinarily precise astrometry, allowing for highly refined dynamics. These data also provide detailed information on asteroid shapes and spin states (Scheeres *et al*. 1996), which are critical for mission planning. Radar data are also important to characterizing satellites and evaluating the magnitude of the Yarkovsky effect (Chesley *et al*. 2003).

3.1.3 Thermal Inertia

Thermal IR spectroscopy can be used to characterize the surface properties of asteroids. In particular, knowledge of the thermal inertia of asteroids is used to detect the presence or absence of regolith on the surface. Objects covered with fine dust possess a low thermal inertia while bare rock has a high thermal inertia. Thermal inertia studies confirm that many small 200-1000 meter diameter asteroids possess sufficient regolith to support sample return (Delbo *et al*. 2002).

Combined thermal and visible observations solve independently for albedo, giving a constraint on size and (via the light curve) shape.

3.1.4 Rotation State

The rotation period provides information on the internal and surface properties of an asteroid. Rotational studies of thousands of asteroids with diameters greater than ~200 meters has uncovered only 2 objects with periods less than 2 hours (Warner *et al.*, 2009). This result suggests that nearly all large asteroids are rubble piles held together by self-gravity. Conversely, most asteroids with diameters smaller than ~150 meters have rotation periods much shorter than 2 hours, suggesting that they are coherent bodies. By identifying "rubble pile" asteroids with rotation periods above the break-up limit we can identify asteroids with freshly exposed surface regions due to regolith movement.

3.2 Instrumentation for Laboratory Analysis of Returned Samples and Data Archiving

The top priority mission for the study of primitive Solar System bodies should be sample return from a carbonaceous asteroid. A strong analytical community is essential to derive maximum science benefit from such a mission. Training the next generation of cosmochemists and improvement of laboratory techniques for the analysis of planetary materials is essential to obtain new information and perspectives on materials from primitive bodies. NASA should maintain a strong sample-analysis program to support instrument development, laboratory facilities, and the training of researchers through R&A programs such as Cosmochemistry, Origins of Planetary Systems, Exobiology, and the Laboratory Analysis of Returned Samples. All NASA-returned extraterrestrial materials should be curated through the well-established ARES facility at JSC. Since sample analysis naturally lends itself to broad international collaboration, other space agencies such as ESA and JAXA should develop similar sample-handling and distribution facilities. Furthermore, data obtained from analysis of returned samples should be treated in a manner similar to that from spacecraft-based instruments and archived for future researchers in the Planetary Data System.

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