# Astro2020 Science White Paper

# Origins Survey of Primordial Relics: ELTs Reveal Compositional Variation across the Solar System

**Thematic Areas:** X Planetary Systems ☐ Star and Planet Formation
☐ Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics
☐ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☐ Galaxy Evolution ☐ Multi-Messenger Astronomy and Astrophysics

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**Abstract (optional):**
ELTs (e.g., GMT, TMT) will provide unprecedented capabilities to explore the formation and evolution of our Solar System. The two main projects to be carried out are (1) a spectral survey of faint primitive objects throughout the Solar System and (2) the creation of geologic maps of the largest primordial bodies in the inner and outer Solar System. In both cases, the data sets will provide enormous scientific return and significant legacy value.

*This white paper presents a series of science investigations that can be carried out with ELTs (e.g., GMT, TMT) that would help reveal the origin of our Solar System through observations of small bodies (asteroids, comets, and the like).*

The most primitive objects in our Solar System are generally found beyond the Main-belt of asteroids: Hilda and Trojan asteroids, Centaurs, Kuiper Belt objects (KBOs), and comets. These bodies formed approximately 4.6 billion years ago at the time of our Solar System's formation and have largely been undisturbed since then. Therefore, their compositions provide a fossilized record of the chemical make-up of our planetary system during its origin.

In the era of planet formation larger bodies were formed from the accumulation of many smaller bodies. This accretionary process had geophysical and geochemical consequences as material from multiple small planetesimals mixed and resulted in the heating and differentiation of larger bodies, thereby erasing the signature of their primordial compositions. Thus, the most primitive of these early planetesimals are likely to be the smallest. Because these are the faintest, they are also the most difficult to physically characterize.

Beyond the Main-belt of asteroids at 4 and 5.2 AU one first encounters the Hildas and Trojan asteroids, respectively. These populations have physical properties that are distinct from the main belt and from each other (but similar to each other at the smallest sizes). The origin of these two populations remains unclear. Giant planet migration scenarios may offer an explanation of why Hildas and Trojans look different from the main belt [2]. Dynamical models [6, 8, 9] predict an origin in the Kuiper belt, with subsequent scattering inward to their present locations. However, if they formed in their present locations, an alternative explanation is that these objects sample the materials that formed the cores of Jupiter and/or Saturn [7].

As primordial objects, Hildas and Trojans are time capsules that preserve the chemistry of the early Solar System's protoplanetary disk (PPD) in the region in which they formed. At first glance, they seem to fit neatly into a paradigm in which macromolecular organic solids were a significant condensate in the middle part of the solar nebula and now darken the surfaces of distant asteroids, but no direct evidence for organics has yet been detected [3, 10, 4]. Presently, the only features detected in spectra of Trojan surfaces are due to fine-grained silicates, whose mineralogy may be closer to that of comet grains than typical stony asteroids (Emery et al. 2006). Comparisons of Trojans to comets and other outer Solar System small bodies are common, given their similarly dark, spectrally red surfaces.

Centaurs are primordial objects with semi-major axes between the orbits of Jupiter and Uranus (5-30 au). There are presently $\sim$450 known Centaurs in this region, but they are thought to be relatively recent ($< \sim$10 Myr) "escapees" from the Kuiper belt on their way to becoming Jupiter family comets (JFCs). Their proximity, compared to the Kuiper Belt, makes them easier to observe using the high spatial resolution capability of TMT. Given their origin in the belt and their dynamical evolution into JFCs, they provide convenient compositional markers between comets and their original reservoir.

The rings and small inner moons of Uranus are quite dark, in contrast to the major moons of Uranus. Broad-band near-infrared photometry also suggests that the ice bands are much weaker for the small moons and rings than they are for the larger moons, implying distinct composition. This could mean that the rings and small moons are more heavily polluted by interplanetary debris or perhaps the material in the rings and small moons represents the bulk composition of the materials around these planets while the surface materials on the larger moons have been processed in some way. More detailed spectra would likely address this mystery.

If observation sensitivities allow, previously undetected rings and/or moons of the outer planets may be discovered. Such structures and objects often open new windows onto the current state of their host planetary systems, and/or onto the system's history.

Kuiper Belt Objects (KBOs) are rocky/icy bodies that orbit outside the orbit of Neptune; Pluto is one of the largest objects in this class. Within the KBO population there are several different formation locations, with commensurately different compositions implied and to be probed. Many of these are large, and have undergone interior processing and thus provide a glimpse of the primitive solar system as it was evolving.

Comets are kilometer-scale volatile-rich bodies that formed outside the solar system's snowline. Because of their small size, they have not been thermally processed over the age of the solar system and they preserve a chemical fingerprint of the disk chemistry. There are several dynamical reservoirs today for comets: the short period JFCs which likely formed in the Kuiper belt, and the long period comets which represent planetesimals that formed in the vicinity of the giant planets that was subsequently scattered into the Oort cloud where it has been stored in a thermal deep freeze until the present when perturbations inject these objects into the inner solar system. Some of these pass close enough to the giant planets to become the Halley-family comets. The Rosetta mission in-situ exploration of comet 67P/Churyumov Gerasimenko showed not only that this comet represented a primitive planetesimal but that it likely preserved some of its pre-solar heritage.

Manx comets are objects on long-period comet orbits with minimal or no activity [5]. Two so far have been seen to have spectral reflectivity consistent with inner solar system rocky material. It is likely they represent material that was ejected from the inner solar system during the planet formation process. Different dynamical models make very different predictions about the amount of material that could be ejected to the Oort cloud from the inner solar system (e.g. models with major giant planet migration, like the Grand Tack, are more likely to eject inner solar system material).

The physical and dynamical properties of these primordial objects enable key tests of competing scenarios for the evolution of the early solar system. ELTs will offer, for the first time, the opportunity to measure the compositions of small bodies in the outer Solar System.

Distinguishing between small body surface composition classes is straightforward. Diagnostic features for minerals require only low-resolution spectra (or filter photometry). At visible wavelengths, most surfaces have few features. There is a weak (1% depth) feature centered at 0.7 $\mu$m indicative of hydration, and inner solar system rocky material has a 1-micron absorption feature. The near-infrared (0.8-2.4 $\mu$m) spectral region is the most diagnostic for separating general compositional classes, including mineral surfaces and ices (See Figure 1). The addition of visible wavelengths (0.4-0.8 $\mu$m) provides additional diagnostic power, and mid-infrared (2.5-5.0 $\mu$m), if possible, completes the range of wavelengths that are most useful. Composition of an asteroid can be best determined through moderate resolution (R$\sim$1,000) spectroscopy in the near-infrared (1–2.5 $\mu$m; NIR), where most important ices and organic materials show diagnostic features.

The IRIS instrument with its diffraction limited imaging and spectroscopic capabilities make it ideal to study the actual shapes and composition of Centaurs, resolving complex structure such as the rings around Chariklo [1] that have a diameter of $\sim 0.1''$. The increase in sensitivity will enable us to characterize several new Centaurs as small as 20km in size at a distance of 10 AU and larger ones further away

Finally, studies of the largest minor bodies in the Solar System allow a comparative probe to understand planetary system formation. Recent work has shown that ground-based telescopes (VLT) can produce near-spacecraft quality geologic maps of the largest asteroids (See Figure 2). ELTs will produce revolutionary insight into the structure, properties, and evolution of minor bodies in the Solar System by providing order(s) of magnitude improvements on these disk-resolved maps. Furthermore, disk-resolved imagery of outer Solar System objects offers a completely new view on the evolution of these most distant objects as a probe of the formation mechanisms in the outer Solar System. To date we have only seen two (soon, three) outer Solar System objects as resolved bodies (Pluto and Charon; soon, Ultimate Thule). A spectral map (as from an IFU) would be the most powerful data set — short of a visiting space mission — for these large primordial bodies.

The science goals described above can be met with ELTs (e.g., GMT, TMT). The main technical requirements are (1) a long-slit spectrograph in the infrared at moderate resolution and (2) an AO-enabled imager, and preferably an IFU. These would provide, respectively, spectra of faint primitive bodies and disk-resolved images (and spectra, in the case of an IFU) of large primordial bodies.

The experimental design is difficult to define. Ideally, for the spectra study of many unresolved bodies, some $\sim$100 bodies in each dynamical class would be observed so that differences among these could be detected rigorously.

For the disk-resolved study, there would be at least 100 objects in the Solar System (both in the main asteroid belt and in the outer Solar System) that can be mapped with the superior resolution offered by ELTs, and each of these target bodies should be observed to generate cosmochemical and geological maps of primordial bodies in our Solar System.

The legacy value of such an observing program is that both the spectral study and the geologic mapping will be completely unique data sets that will not have any parallel for decades. Thus, any study of the formation of the Solar System and of other planetary systems will need to include these data as anchor points for general theories.

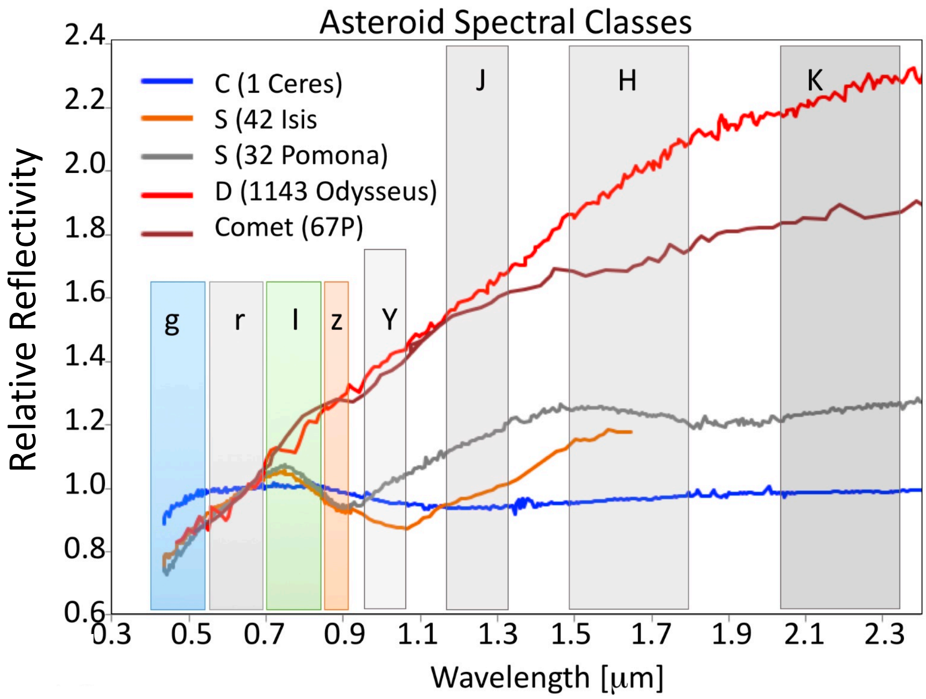


Figure 1: Spectral reflectivity of non-icy small bodies showing that low resolution spectra is sufficient to distinguish between different classes.

Figure 2: *Left:* Ground-based VLT/SPHERE image of Vesta, the largest asteroid in the Solar system. *Right:* Global image of Vesta from NASA's Dawn mission. Images from `https://www.eso.org/public/images/potw1826a/`

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