ASTEROID RECONNAISSANCE FOR RESEARCHING ORGANICS AND WATER IN THE SOLAR SYSTEM (ARROWS^2): A DEEP SPACE SMALLSAT MISSION (CONCEPT) TO PRIMITIVE ASTEROIDS. D. Takir[1], J. Mulqueen[2], J.C. Castillo-Rogez[3], [1]SETI Institute, Mountain View CA, United States; [2]NASA Marshall Space Flight Center, Huntsville, Al, United States; [3]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, United States.

ARROWS^2 Objectives: The Asteroid Reconnaissance for Researching Organics and Water in the Solar System ARROWS^2 mission would (1) investigate the abundance and distribution of water and organics in the inner and outer main asteroid belt (0.5 < a < 5 AU), (2) test the current thermal and dynamical models for the origin and evolution of primitive objects (e.g., [1], [2]), and (3) place the returned pristine samples from sample return missions (e.g., NASA's OSIRIS-REx [3], JAXA's Hayabusa2 [4]) in context with the larger asteroid population.

ARROWS^2 Science Targets: ARROWS^2's science targets were selected based on our extensive study of primitive asteroids using ground-based observations. Table 1 includes some primary primitive asteroids that we would consider for our initial concept study, including the potentially hazardous asteroid 2008 EV5. EV5, like Bennu (OSIRIS-REx's asteroid target) and Ryugu (Hayabusa2's asteroid target), is a primitive asteroid possibly originating from the inner main belt that made its way into the NEO space via many orbital resonances the giant planets[5]. We would use additional primitive asteroids from [6] as backup targets as needed to optimize our trajectory design for ARROWS^2 while addressing our science goals and staying under the mission cost limit.

ARROWS^2 Science Rational: Water in many forms has been discovered throughout the Solar System (e.g., [7], [8]), and is thought to be condensed beyond a certain distance from the Sun, called the snow-line, within the asteroid belt [9]. Water has also been discovered bound in minerals (e.g. phyllosilicates) on several primitive (carbon- and water-rich) asteroids in the inner and outer main asteroid belt (e.g., [6]). Organic compounds were also discovered on the surface of primitive asteroids (e.g., [7]). Water and organics are considered some of the major planet-building elements in the protoplanetary disk and are necessary for life. Asteroids bearing water and organics may have been responsible for seeding this material on the early Earth, allowing life (as we know it) to develop [8].

Primitive asteroids are scientifically compelling because they were formed early in the evolution of the Solar System. Their original composition is thought to be a mixture of anhydrous minerals and ice. Heat released by decay of ^{26}Al melted the ice, and the liquid water reacted with olivine and pyroxene to form hydrated phyllosilicates [1]. In this model, asteroids nearer the Sun accreted earlier, and thus incorporated more ^{26}Al. Conversely, the "Grand Tack" model suggests that primitive asteroids originated among the giant planets, with later delivery to their current locations in the main asteroid belt by the migration of Jupiter [2]. ARROWS^2 SmallSats will investigate the compositional and geological processes of primitive targets from different asteroid families (e.g., Polana, Hygeia, Hilda), to illuminate the origin, evolution, and distribution of water and organics in the Solar System.

30 primitive asteroids in the 3-4 µm spectral region (where water and organics can be spectrally detected) have been observed using NASA IRTF and Gemini North telescopes, adding to the already 50 primitive asteroids previously observed by [6, 9]. Thus far, the investigation has allowed for the identification and distribution of at least three different 3-µm spectral hydrated groups, each of which is presumably related to distinct surface mineralogy [10]. However, asteroid spectra measured with ground-based telescopes are affected by strong absorptions by water vapor in Earth's atmosphere. Therefore, ARROWS^2 is needed to put ground-based observations in a broader context to address the questions of the formation and origin of the Solar System. ARROWS^2 would provide data, unavailable from ground-based observations, to test the thermal and dynamical models. ARROWS^2 would also provide a unique dataset to put the analysis of the returned (localized) sample from NASA's OSIRIS-REx target (Bennu) and JAXA's Hayabusa2 target (Ryugu) in a global perspective. Please see ARROWS^2's Traceability Matrix in Table 2.

ARROWS^2 Mission Concept Approach: We would generate an optimized and feasible trajectory concept for ARROWS^2 that would allow us to achieve our science objectives while staying under the total cost limit of the mission. The ARROWS^2 SmallSats would likely be most feasible as secondary payloads on a main SMD planetary mission whose primary target is some suitable nearby body, most likely Mars or Jupiter due to the relative regular launch frequency to these planets. In our mission concept study, ARROWS^2 SmallSats would be deployed from the Evolved Expendable Launch Vehicle Secondary Payload Adapter (ESPA) ring on the primary payload's launch vehicle upper stage and use integral propulsion to reach the target asteroids.

We would investigate and assess SmallSats subsystem options, including propulsion, power, control, communications and data handling. The ARROWS[2] SmallSats concept would build on NASA's MSFC experience developing Fast Affordable, Science and Technology Satellite (FASTSat) minisatellite (Figure 1). MSFC is also currently developing CubeSat propulsion technologies such as Interplanetary Iodine Powered Satellite (iSat) that would be directly applicable to deep space missions (Figure 2). Figure 3 shows notional ARROWS[2] SmallSat Concept Based on MSFC iSat Concept. The Iris Communications Cube, which would be supplied by NASA as Government Furnished Equipment (GFE), would perform communications and data transmission functions. The concept definition study would also include analysis of deep space thermal and radiation environments and the design implications on the mission spacecraft.

References: [1] Grimm R.E. and McSween H.Y. (1993) *Science* 259, 653-655. [2] Walsh K.L. et al. (2011) Nature *475*, 206-209. [3] Lauretta D.S. et al. (2017) *SSR*, 212, 925-984. [4] Tsuda Y. et al. *Acta Astronautica* 91:356-362. [5] Bottke W.F. et al. (2015) *Icarus* 247, 191-217. [6] Takir D. and Emery J.P. (2012) *Icarus* 219:641-654. [7] Rivkin A.S. and Emery J.P. (2010) *Nature* 64, 1322-1323. [8] Küppers M. (2014) Nature 555, 525-527. [9] Lunine I.J. (2006) *in Meteo. in the Solar System II.* Ariz. Univ. Press, pp.309-319-624. [8] Chyba C. and Sagan C. (1992) Nature 355, 6356, 125-132. [9] Takir D. et al. (2015) *Icarus* 257, 185-193. [10] Takir D. et al (2013) *MPS,* 48, 1618-1637.

Table 1. ARROWS2's science targets physical properties (http://ssd.jpl.nasa.gov).

Primitive Asteroid	Spectral Class	Family	*a* (AU)	*i (deg)*	*e* (deg)
2008 EV_5	-	-	0.96	7.43	0.08
142 Polana	F	Polana	2.42	2.24	0.13
2 Pallas	B	Pallas	2.77	34.84	0.23
52 Europa	CF		3.10	7.47	0.11
24 Themis	C	Themis	3.14	0.75	0.12
10 Hygeia	C	Hygeia	3.14	3.83	0.11
65 Cybele	P	Cybele	3.43	3.56	0.11
153 Hilda	P	Hilda	3.98	7.82	0.14

Table 2. ARROWS[2]'s Traceability Matrix.

Major Themes	Science Questions	Measurements	Instruments
Origin and Evolution	Where in the Solar System did primitive asteroids originate? Any evidence of secondary processes (e.g., metamorphism, aqueous alteration)? Any evidence for dynamical mixing? Any evidence for impact cratering history Any presence of comae, satellites, or dust in the target neighborhoods?	Mineralogical composition Compositions of ices and relative abundances of ice phase Determine the role of impacts from crater counts and colors of materials in ejecta blankets around craters	Spectrometer Camera Radio science experiment
Chemical and Physical Structure	Physical characteristics of the targets? Any evidence for water, organic material?	Size, Shape, Density, and Spin rate? Absorption due to 3.3-µm, 3.4-µm C-H stretching in aromatics and aliphatic. Absorption due to 0.7-µm and 3-µm in water and water-bearing minerals	Camera Radio science experiment Spectrometer

Figure 1. NASA MSFC's FASTSat minisatellite.

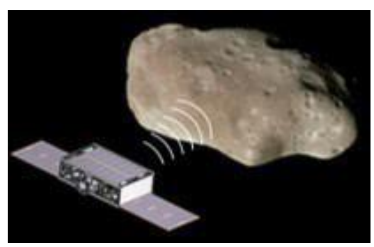
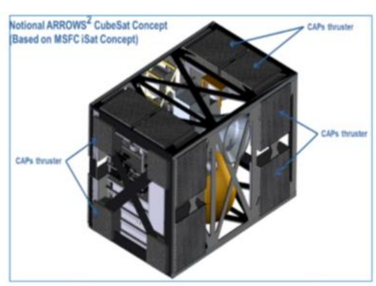


Figure 2. NASA's iSat will be the first CubeSat to demonstrate high change in velocity from a primary propulsion system by using Hall thruster technology and iodine as a propellant (NASA/MSFC).



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