SPACECRAFT PENETRATOR FOR INCREASING KNOWLEDGE OF NEOS (SPIKE). E. Asphaug[1], J. Baker[2], M. Choukroun[2], R. Furfaro[3], P. Sava[4], D.J. Scheeres[5], S.R. Schwartz[1], T. Swindle[3], J. Thangavelautham[1] [1]School of Earth and Space Exploration, ASU, 781 E Terrace Rd, Tempe, Arizona, 85283 (easphaug@asu.edu), [2]JPL, Pasadena, CA, [3]U Arizona, Tucson, AZ, [4]CSM, Golden, CO, [5]CU, Boulder, CO.

Introduction: Hundred-meter-class asteroids, remnants of the precursors to planets, are important science objects and represent the peak of the impact hazard. They are also potential targets for human exploration and resource utilization. Their extremely low gravity allows us to devise a repeat-landing mission that requires no chemical propulsion, thereby saving on cost and risk, and allowing for multiple subsurface-probing measurements at multiple asteroids using an ESPA-class solar electric propulsion (SEP) spacecraft.

Mission Concept. A potential spacecraft design is based around the JPL Micro Surveyor that has a mass of 75 kg (wet) including two science instruments that access >10 cm beneath the surface. The spacecraft is estimated to have a delta-V of 5 km/s sufficient for performing a tour of 2 small NEOs. After surveying the first asteroid, the spacecraft is directed into a precisely guided free-fall, impacting slowly (v~10 cm/s) under milligravity (a_g~0.1 mm/s^2) into a selected patch of regolith (Fig. 1). The bus comes to rest vertically on top of the Science Instruments Module which is deployed at the end of a ~3 m rigid extensible truss (Fig. 2). The base of the SIM has two penetrators that are pushed into the subsurface to enable science that has never been done at an asteroid: *subsurface volatile and organics determination* and *seismology*.

A single landed spacecraft can be much lower risk and cost than an asteroid orbiter that deploys discrete landers to do the same science. A sub-lander that measures compositional and seismic properties at depth introduces weak links in thermal, comms, ACDS and power, and thus has lower overall capability. But unlike a compact hopper that can land in free fall and tumble around the surface, SPIKE must touch down in a controlled manner and not tip over. The very low velocity landing dynamics is forgiving to a “grab-and-go” approach, that is sufficient for our science, but longer duration landings are possible. We are studying the degree to which spacecraft motion, asteroid motion, solar wind and gravity can be balanced using standard reaction wheels, and if necessary, the gimbaled Hall thruster on that pushes gently down, to enable repeated landings of arbitrary duration without requiring chemical propulsion.

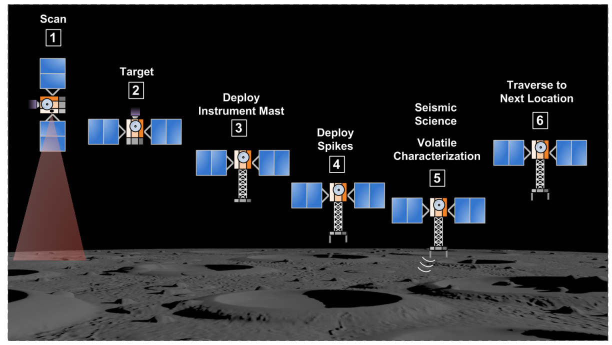

Figure 1. The science mission begins with a survey phase using a camera to determine asteroid rotation state and gravity and look for suitable landing locations. Descent is in free-fall. For take-off a 1 cm/s push-off is sufficient to send the spacecraft on a sub-orbital hop, giving time (tens of minutes) for the spacecraft to turn and fire its Hall thruster, eliminating the need for chemical propulsion.

Target Requirements. The target asteroid(s) must be smaller than about 1 km so that the free-fall will not damage the spacecraft, and so that the reliable but low thrust SEP motor can accelerate away from the asteroid. For example, free fall of the NEAR spacecraft onto the surface of asteroid Eros was around 4 m/s. Not only is this speed difficult for this kind of spacecraft to bear, but getting up off the surface requires more thrust than a Hall thruster can deliver, approx. 0.3 mm/s^2 for our spacecraft configuration. For an asteroid smaller than 1 km, the thrust exceeds the weight by a factor of several, so all that is required is for the spacecraft to hop mechanically from the surface, using the same damping mechanism that is used to soften the landing, at merely 1 cm/s. This weak hop sends the spacecraft

Science Goals	Objectives	Observables	Payload Requirement	Mission Requirement
Volatiles & Organics	Bound and free water content of regolith	Abundance of H_2O ice in regolith	• Gas chromatograph • Mass spectrometer	Collector to acquire volatiles and organics from >30 cm below surface
	Spatial and chemical distribution of organic species	Abundance and composition of carboxylic acids, PAHs and amino acids		
Seismology	Global and local active seismic experiments	Seismic reflections detected for >1 minute	• Geophone • Thumper • Vibrator • Accelerometer	Sensors buried to >30 cm depth into seismically competent material
	Force sensing	Spring force; accelerometers; penetration depth		

on a suborbital arc 10-100 m from the asteroid, providing tens of minutes to rotate and depart on an escaping trajectory exceeding the small gravity, either to prepare for another landing site or to depart for a new asteroid.

For penetrator science the target requires a patch of regolith ~1 m deep. Ignoring friction, the work done in stopping the spacecraft ($\frac{1}{2}mv^2$) equals the energy required to crush and/or deform regolith, so $d = mv^2/2A\sigma_c = (50\text{kg})\ (0.2\text{m/s})^2\ [2(1000\text{N/m}^2)(10^{-3}\text{m}^2)]^{-1} \sim$ 1 m, inversely with σ_c. Because gravity is so weak, shear strength does not increase much with depth like it does on the Moon. A force of ~1 N is sufficient to push in the spikes; by comparison the truss we are considering can withstand 20 to 180 N depending on the load point. If interparticulate cohesion is much weaker, then the spike will penetrate deeper; the Science Instruments Module has substantial cross section (~0.5 m^2) so that even a loose dust pond (σ_c~100 N/m^2) would stop it in a few cm, leaving only the penetrators fully in the subsurface. For stronger materials the impact velocity can be accelerated, while for weaker materials the spacecraft can fall from lower altitude at lower velocity. These operations can be tested rigorously in Earth gravity using a cantilevered pendulum.

Mission Significance. A spacecraft lander without chemical propulsion will be a remarkable advancement for asteroid exploration, given the extremely high reliability of SEP compared to chemical systems, especially for multiple-rendezvous missions lasting years. The mission responds to the call from the National Research Council's study *Defending Planet Earth: Near-Earth Object Surveys and Hazard Mitigation Strategies Final Report*, which seeks "dedicated spacecraft missions to NEOs providing extended periods for observations and investigation close to NEOs to obtain detailed characterizations of their rotational motions, masses, sizes, shapes, surface morphology, internal structure, mineral composition, and collisional history." The 2014 *NASA Science Plan* notes that in the *NASA Authorization Act of 2008*, Congress mandated that "tracking and characterizing near-Earth objects greater than 140 meters in diameter" be a specific programmatic activity of NASA. The SPIKE mission promises to characterize the surfaces and interiors of multiple NEOs of the size deemed most important for hazard mitigation. Probing the interior structure and chemical abundances (which include volatiles and organics) of these bodies will shed light on their collisional evolutionary history and address questions posed by NASA's Earth and space science program including *"How did our solar system originate and change over time?"* And *"How did life originate, and are we alone?"*

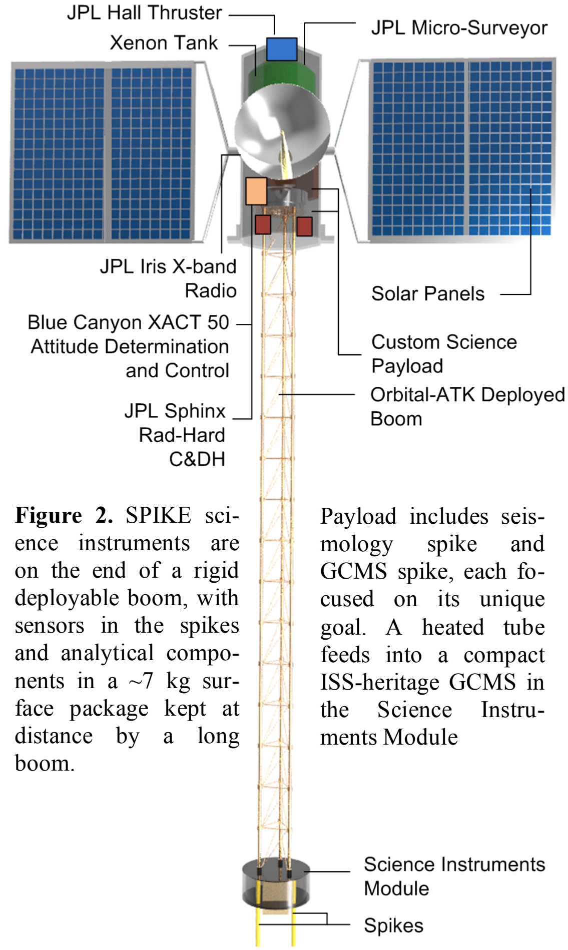

Figure 2. SPIKE science instruments are on the end of a rigid deployable boom, with sensors in the spikes and analytical components in a ~7 kg surface package kept at distance by a long boom. Payload includes seismology spike and GCMS spike, each focused on its unique goal. A heated tube feeds into a compact ISS-heritage GCMS in the Science Instruments Module

Target Requirement	Probability
First target must be primitive (B, C or D)	Certain; many candidates
Regolith bed at least 1-m deep exists somewhere on the asteroid	Almost certain for NEOs >100 m diameter; can be confirmed by groundbased observations
Clast sizes are <30 cm diameter in the target footprint (dust ponds, gravel beds ideal)	Unknown for the smallest (50–100 m) bodies considered, certain to be found for asteroids 0.3–1 km
Regolith cohesion < 10 kPa in the target footprint	Could be greater if ice-cemented materials (unlikely), or as low as 10–100 Pa
Surface g < 0.3 mm/s^2 for gentle landing and to allow SEP-powered escape	Certain for <1 km diameter