ASSESSING THE AVAILABILITY OF LOW DELTA-V TARGETS FOR ISRU DEVELOPMENT AND WATER EXTRACTION. R. Jedicke[1], M. Chyba[2], M. Granvik[3], T. Haberkorn[4], G. Patterson[5], and J. Sercel[6]. [1]University of Hawai`i (Institute for Astronomy, 2680 Woodlawn Dr., Honolulu, HI, 96822, jedicke@hawaii.edu), [2]University of Hawai`i (Department of Mathematics, 2565 McCarthy Mall (Keller Hall 401A), Honolulu, Hawaii 96822, chyba@hawaii.edu), [3]University of Helsinki (Department of Physics, P.O. Box 64, 00014 University of Helsinki, Finland, mgranvik@iki.fi)), [4]University of Orléans (MAPMO-Fédération Denis Poisson, 45067 Orléans, France, thomas.haberkorn@univ-orleans.fr), [5]University of Michigan (DCMB, 1600 Huron Pkwy, Building 520-3369, Ann Arbor, MI, 48105, gpatter@umich.edu), [6]TransAstra Corporation (ICS Associates Inc., Lake View Terrace, CA, 91342, sercel@transastracorp.com),

Introduction: Nature delivers water and ore bearing asteroids to the inner solar system (near-Earth objects; NEO) through gravitational interactions with the planets and the subtle nudging of thermal forces [1]. The objects in the low delta-v tail of this distribution are obvious targets for economically viable ISRU. We have used the recently determined size and orbit distribution of the NEOs [2], in combination with their albedo [3], density [4], and water content estimates [5] to calculate the low delta-v distribution for water-bearing NEOs and the amount of water available in those targets. In addition, we calculated the delta-v distribution of the population of 'minimoons' – natural small asteroids that are temporarily captured from the NEO population for an average of 9 months within the Earth-Moon system.

Small near-Earth Objects: The NEOs are the population of asteroids and comets that have perihelia of <1.3 au. The asteroids within the population derive from the main belt of asteroids between Mars and Jupiter while the cometary ~5% of the population are from the Jupiter-family comets (JFC). Some long period comets, that may be large and have high water content, are also NEOs but they enter the inner solar system infrequently and at high speeds making them difficult ISRU targets. The absolute magnitude (a proxy for size), semi-major axis, eccentricity and inclination distribution of the NEOs has been measured for objects down to diameters of about 50 m [2] including a determination of the main belt 'source region' from which they derive. Since the source regions' asteroids' taxonomic distribution have also been measured [6] we have calculated the probability that an NEO on a particular orbit is of a specific taxonomy (mineralogy). Finally, we have developed a simple, accurate, and conservative technique to estimate the delta-v required to bring an asteroid's resources back to lunar distant retrograde orbit (LDRO). We find that there are about 1,000 small NEOs from which it is possible to deliver resources to LDRO with delta-v <2 km/s (Figure 1).

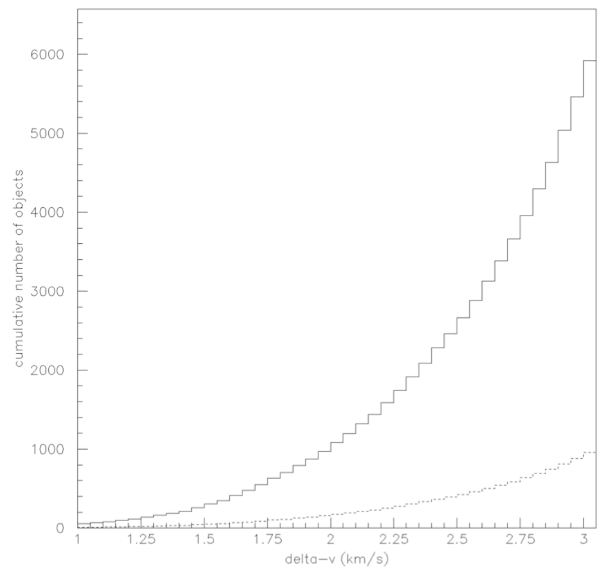

Figure 1 – The cumulative number of objects with diameter <4 m as a function of the delta-v required to deliver resources from the asteroid to LDRO. The solid line represents all objects in the NEO population and the dashed line represents C-class asteroids that contain water-bearing minerals

Minimoons: For the first time, ten years ago a small asteroid was discovered that was gravitationally bound within the Earth-Moon system (2006 RH_{120}; [7]). Six years later, theoretical modeling of the capture mechanism of these 'minimoons' from the NEO population [8] suggests that there must be a transient population of small asteroids in the Earth-Moon system at all times for which the largest object in the steady-state population is 1 to 2 m in diameter (at a few meters diameter, 2006 RH_{120} was a once-in-a-decade event). We think the minimoons provide an excellent opportunity for developing and testing rapid-response ISRU technologies on targets that are available on short duration mission trajectories at very low delta-v. Towards that end we have developed techniques to optimize the delta-v for ISRU missions to both the actual minimoon 2006 RH_{120} [9] and a large set of synthetic minimoons [10] assuming that the rendezvous spacecraft is maintained in a halo 'holding' orbit around the Earth-Moon L1 or L2 point. Most minimoons are accessible with delta-vs of <1 km/s and a retrieval mission including a return to the parking halo orbit has been designed for 2006 RH_{120} for a similar delta-v [9].

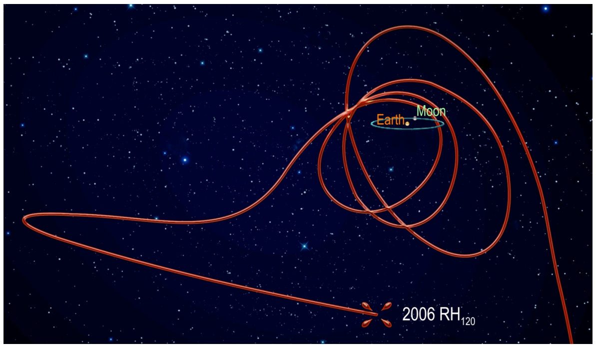

Figure 2 – The trajectory of the minimoon 2006 RH_{120} during its roughly 9 month sojourn in the Earth-Moon system.

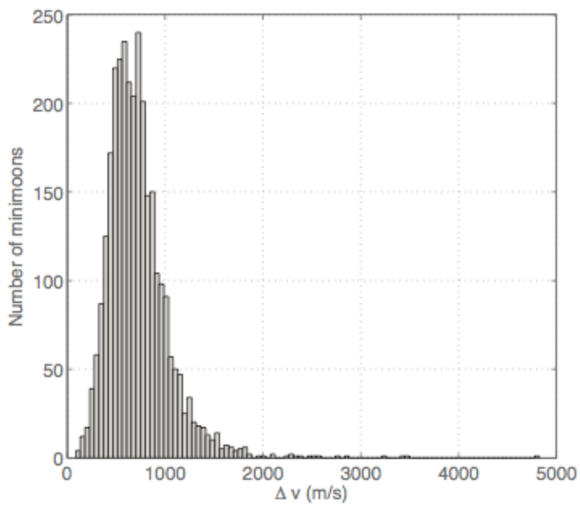

Figure 3 Incremental delta-v distribution for 3-burn trajectories from an Earth-Moon L1 halo orbit to 3,000 synthetic minimoons [Patterson thesis].

Discussion: Our studies show that there are low delta-v minimoons and NEOs that could be excellent targets for testing ISRU technologies and for jump-starting the ISRU industry of mining water from asteroids and delivering it to LDRO. The difficulty lies in detecting these small, water and metal rich asteroids in an economically viable manner. Doing so requires the development of an asteroid survey(s) that can efficiently identify the small asteroids of ISRU interest and determine their orbits accurately enough to enable ISRU missions. The current generation of asteroid surveys are not discovering and characterizing the small asteroids fast enough for developing an ISRU industry utilizing small NEOs but it is possible that the next generation of ground- and space-based surveys [11] will do so.

References: [1] Granvik, M., et al. (2012) *AAS/Division for Planetary Sciences Meeting Abstracts*, 44, 305.03. [2] Granvik, M., et al. (2016) *Nature*, 530, 303-306 [3] Thomas, C. A., et al. (2011) *The Astronomical Journal*, 142, 85. [4] Carry, B. (2012) *Planetary and Space Science*, 73, 98-118. [5] Mason, B. (1963) *Space Science Reviews*, 1, 621-646. [6]. DeMeo, F. E., & Carry, B. (2013) *Icarus*, 226, 723-741 [7] Kwiatkowski, T., et al. (2009) *Astronomy and Astrophysics*, 495, 967-974. [8] Granvik, M., et al. (2012) *Icarus*, 218, 262-277. [9] Chyba, M., et al., (2016) to appear in *Recent Advances in Celestial and Space Mechanics*. [10] Patterson, G., (2015) Ph.D. Thesis, University of Hawai`I, [11] Jedicke, R., et al., (2015) *Asteroids IV*, 795-813