Robotic Asteroid Prospector

Marc M. Cohen[1]
Marc M. Cohen Architect P.C. – Astrotecture™, Palo Alto, CA, USA 94306-3864

Warren W. James[2]
V Infinity Research LLC. – Altadena, CA, USA

Kris Zacny,[3] Philip Chu, Jack Craft
Honeybee Robotics Spacecraft Mechanisms Corporation – Pasadena, CA, USA

This paper presents the results from the nine-month, Phase 1 investigation for the Robotic Asteroid Prospector (RAP). This project investigated several aspects of developing an asteroid mining mission. It conceived a Space Infrastructure Framework that would create a demand for in space-produced resources. The resources identified as potentially feasible in the near-term were water and platinum group metals. The project's mission design stages spacecraft from an Earth Moon Lagrange (EML) point and returns them to an EML. The spacecraft's distinguishing design feature is its solar thermal propulsion system (STP) that provides two functions: propulsive thrust and process heat for mining and mineral processing. The preferred propellant is water since this would allow the spacecraft to refuel at an asteroid for its return voyage to Cis-Lunar space thus reducing the mass that must be launched from the EML point. The spacecraft will rendezvous with an asteroid at its pole, match rotation rate, and attach to begin mining operations. The team conducted an experiment in extracting and distilling water from frozen regolith simulant.

Nomenclature

C-Type = Carbonaceous Asteroid
EML = Earth-Moon Lagrange Point
ESL = Earth-Sun Lagrange Point
IPV = Interplanetary Vehicle
M-Type = Metallic Asteroid
NEA = Near Earth Asteroid
NEO = Near Earth Object
PGM = Platinum Group Metal
STP = Solar Thermal Propulsion
S-*Type* = Stony Asteroid

I. Introduction

THE central objective of Robotic Asteroid Prospector (RAP), Phase 1, was to determine the feasibility of mining asteroids. Ideally, this determination should be based on economic, technical, and scientific considerations and lead to the conceptualization of initial robotic and later human asteroid mining missions. The RAP team began its work from a deeply skeptical perspective on the viability of long-term space industrialization, including the minerals and mining sector. The team posited that for asteroid mining to become feasible, its advocates must make five arguments successfully:

1. That there are accessible, exploitable, and valuable minerals, metals, and possibly H_20 in the asteroids,

---

[1] President and Owner, 4260 Terman Drive #104, Palo Alto, CA 94306, AIAA Associate Fellow, http://www.astrotecture.com. Principal Investigator. This work was funded by NASA Innovative and Advanced Concepts grant NNX12AR04G.

[2] Chief Technology Officer, V Infinity Research LLC, 671 E. Altadena Avenue, Altadena CA 91001. Co-Investigator for Mission and Spacecraft Design.

[3] Vice President, Honeybee Robotics Spacecraft Mechanisms Corp, 398 W. Washington Blvd. #200, Pasadena CA 91103. Co-Investigator for Mining and Robotics.

2. That a sustained market demands exists or will exist on Earth, in space, or both,
3. That the team can develop a transformational mission design to make frequent, repeated missions to an asteroid possible.
4. That the team can design, develop, and produce the innovative spacecraft necessary to carry out the mission, and
5. That the team can develop the necessary robotic mineral extraction, beneficiation, processing, and concentration technologies.

The RAP team made progress on each of these criteria, as follows.

II. Accessible Resources

The RAP team identified water as the commodity most likely to be of value for extraction and sale to customers in space for use as propellant. Water used for Life support is viewed as a secondary market because closed life support systems that recycle water reduce the mass requirements for that resource to a much lower level than expected for water used as propellant. Metals for use in space for large construction projects, such as space based solar power satellites, are a potentially large market but this will not develop until society commits to undertaking such large in-space projects. However it is felt that the demonstrated economics of mining asteroid water could serve as a stimulus for starting those projects and thus create a feedback mechanism that will create and grow the market for in-space use of metals and other raw materials. Platinum group metals (PGM) are the best candidates for potential sale on Earth, however the scope of the undertaking would require returning 10s of metric tons of PGMs to Earth annually. It is also impossible to estimate with any certainty how the PGM market would be affected and whether any new applications for less expensive PGMs would surface. Rare Earth Elements (REEs), although increasingly in demand on Earth, do not appear to be a viable candidate at this time because of the high cost and complexity of processing the ore. Additionally since the current cost of REEs extracted from the Earth is driven by the cost of the environmental remediation associated with that activity there is the very real chance that reducing those remediation costs would be a more cost effective way to increase the supply of REEs than asteroid mining. Additional potential economic resources included scientific samples, regolith for radiation shielding, and processed regolith for agricultural soil.

With respect to where to find these resources, the RAP proposal baselined a set of telescopes in Venus orbit, looking outward from the Sun to identify and track the population of Near Earth Asteroids with far greater precision than currently available. Therefore, the RAP team was delighted when Planetary Resources LLC announced their startup in 2012, with a first phase of deploying the Arkyd space telescopes for this purpose. RAP looks forward to data from advanced versions of the Arkyd that could obtain albedo, rotation and spectrographic data for candidate asteroids.

A. Mineral Economics Strategy

In developing the RAP Work Plan, the team had agreed that mineral economics should play a trail-blazing role to generate the parameters within which the other three disciplines – mission design, spacecraft design, and prospecting/mining/processing must work. However, that leadership role of economics proved a non-starter. We could not find the data, the economic model, or the economic expertise to pursue that approach in a credible manner. Instead, one of the first things we learned was that the second clause of our title: Robotic Asteroid Prospector (RAP) Staged from L1: Start of the Deep Space Economy was vastly more ambitious than we imagined. Instead of concocting our fantasy of an economic-infrastructural demand model of human civilization expanding across the Solar System over the next century, we needed to find an alternative construct that we could validate. The best we could do is to construct a parametric model of the cost of developing and building the spacecraft, flying the mining missions, and paying for it over time at prices that the space and Earth markets could bear. This parametric model appears at the end of the Spacecraft Design chapter below.

B. Asteroids, Meteorites, and Metals

Our knowledge of asteroid composition comes primarily from meteorites found on Earth backed up with spectrophotometric observations of asteroids and orbital analysis that ties specific meteorites to unique asteroid types and families (Figure 1). The collection and analysis of these meteorites gives an extensive inventory of the minerals and metals that may occur naturally on asteroids, which in some respects are simply very large meteoroids.

1. *Families of Metals*

FIGURE 1 shows Fe-Ni meteorites. M-type asteroids are primarily Fe-Ni, with a distinctive emission line at 0.9µ. The sidrophilic Pt group and Au occur in Fe-Ni meteorites. M-type metallic asteroids appear to contain Pt group metals potentially worth billions or trillions of dollars at market (Lewis, 1991). The top prices for platinum group metals are $43.4k/kg for Re and $51k/kg for Pt.

Campo Meteorite Gibeon Meteorite

FIGURE 1. Examples of Fe-Ni Meteorites

2. *Water from Carbonaceous Chondrites*

Carbonaceous chondrites are grouped into at least 8 known groups. The two groups, notably the CM and CI, contain high percentages (3% to 22%) of water, and some organic compounds (Norton, 2002). The presence of volatile organic chemicals and water means that since their formation they have not undergone heating above approximately >200 °C. In fact it is believed that CI (which contain higher fraction of water than CM) have not been heated above 50 °C. Therefore the CI type asteroids would be the best targets for the RAP mission with a goal to acquire water.

3. *Near Earth Objects*

Near-Earth Objects (NEOs) are asteroids and comets that have orbits closely resembling the orbit of the Earth. These asteroids are made up mostly of rock, metals, water and carbon compounds with the exact amounts of these materials being a function of the asteroid's type. These objects are classified by their characteristic spectra, with the majority falling into three main groups: C-type (carbon rich), S-type (stony), and M-type (metallic). FIGURE 2 shows a diagram of M-type NEAs.

NEO asteroids are also referred to as Near Earth Asteroids or NEAs in order to distinguish them from asteroids within the asteroid belt, Trojan asteroids that share an orbit with a planet or moon or comets that have NEO orbits. NEAs can be further subdivided into groups: Atiras, Aten, Apollo, and Amor, according to their perihelion distance (q), aphelion distance (Q) and their semi-major axes (a).

- Atiras orbits are contained entirely with the orbit of the Earth.
- Atens are Earth-crossing NEAs with semi-major axes smaller than Earth's.
- Apollos are Earth-crossing NEAs with semi-major axes larger than Earth's.
- Amors are Earth-approaching NEAs with orbits exterior to Earth's but interior to Mars'.

In addition, another group, called Potentially Hazardous Asteroids are PHAs whose Minimum Orbit Intersection Distance (MOID) with the Earth is less than 0.05 AU (i.e. less than ~7,480,000 km) and whose absolute magnitude is 22.0 or brighter with assumed albedo of 13% (i.e. diameter larger than about 150 m). They are called Potentially Hazardous because they can come close to Earth, although this does not mean that they will certainly impact the Earth, and they are large enough to cause significant global damage should they impact the Earth. There exists some threat though, and hence they are being monitored to determine the probability of their impact with Earth.

FIGURE 3 illustrates the Earth-Sun Lagrange Points (ESL) and the Earth-Moon Lagrange Points (EML). The Lagrange Points will take on great importance in the Mission Design Chapter. So, finally, Trojans are asteroids captured at the triangular Lagrange points at L4 60° ahead or L5 60° behind any planet or moon in its orbit. Jupiter Trojans are well known. A few Mars Trojans have been identified and confirmed as follows:

L4 -- 1999 UJ7
L5 -- 5261 Eureka, 1998 VF31

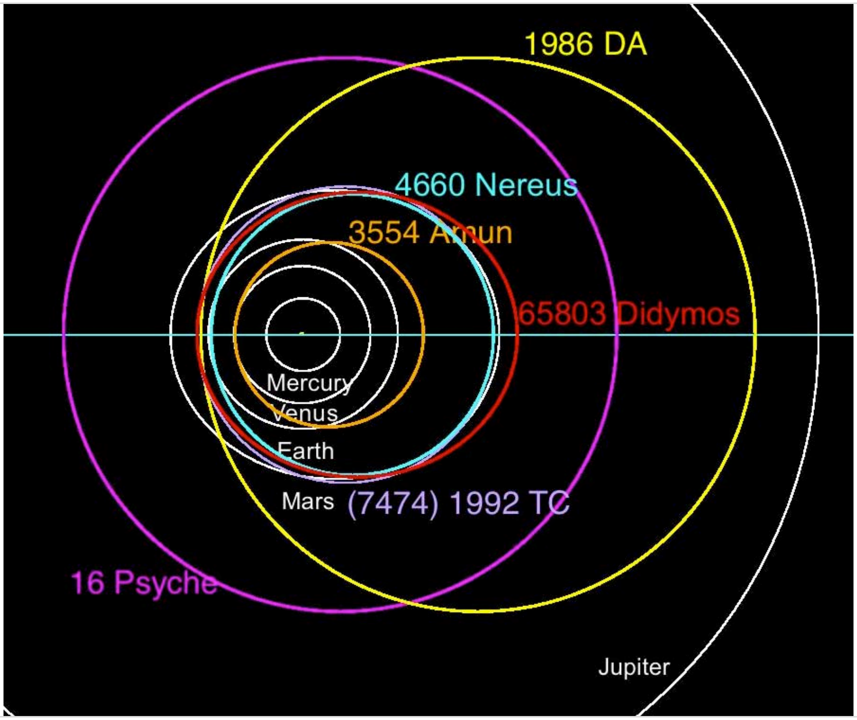

FIGURE 2. Orbits of M-type asteroids with major axes aligned, perihelion to the left.

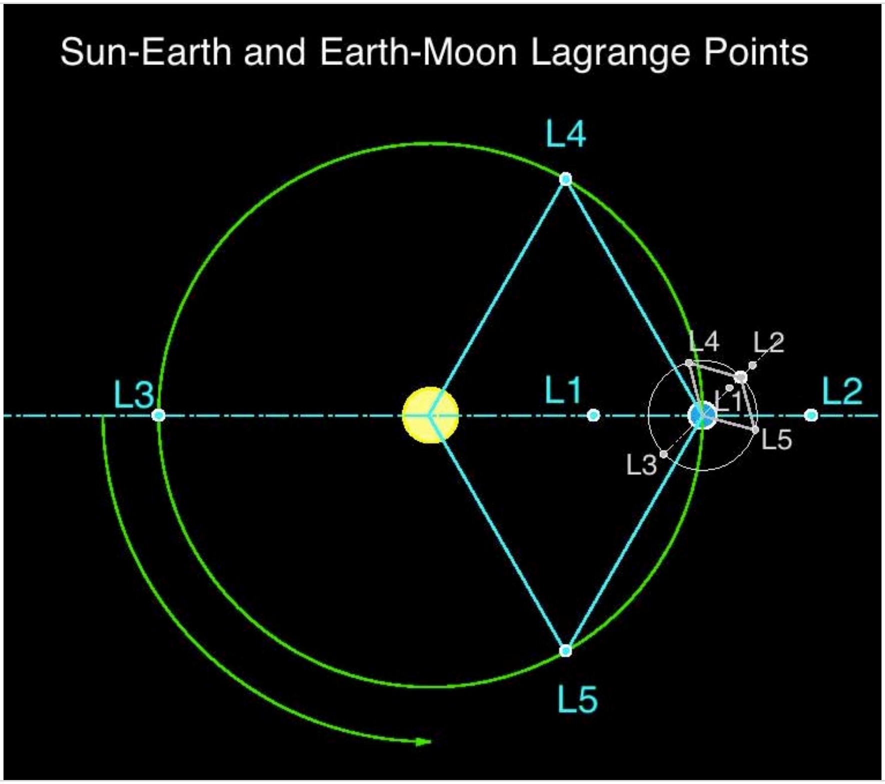

FIGURE 3. Earth-Moon and Earth-Sun Lagrange points.

Most carbonaceous asteroids are thought to have formed in the cold outer planetary system, while most of the rocky asteroids formed in the warmer inner solar system. Asteroids are the remnants from the process that formed the solar system 4.6 billion years ago. They could offer a clue to the chemical and physical constitution of the pre-planetary nebula from which the planets formed since they have not been subjected to the geochemical and thermal processes that have occurred on the Terrestrial planets and moons following their formation.

Asteroids also pose great interest as source of raw materials. Currently, it does not seem to be cost effective to extract resources and bring them back to Earth. However, there appears to be an economic value in processing the resources in situ and using these processed resources in space. Raw materials from M-type asteroids could be used in developing various space structures. Water and carbon-based molecules from C-type asteroids could be used to sustain life and in generating liquid hydrogen and oxygen rocket fuel required to explore and potentially colonize our solar system.

What makes NEAs even more enticing is that unlike asteroids within the Asteroid Belt between the orbits of Mars and Jupiter they have orbits with semi-major axes that are not significantly different from that of the Earth's orbit and thus the energy required to reach them is significantly less than the energy required to reach main belt asteroids. Some NEAs are even easier to reach than the Earth's moon and most others are easier to reach than Mars. Additionally, the mission duration for voyages to most NEAs is much less than would be required for a mission to a main belt asteroid.

Initially, the RAP team was looking primarily at asteroids in the Inner Solar System, inside the orbit of Mars. In a later phase, this attention will expand to the Main Belt, but given the scope of the present contract, the NEAs seem to be the most sensible targets.

FIGURE 2 shows some potential observing targets the inner solar system, with the orbits of several M-type NEAS plus 16 Psyche, the largest known M-type representing the Main Belt. 3554 Amun, best known because of Lewis (1991), may not be high enough density to be metallic. 1986 DA may offer a better prospect in terms of confirmed composition and estimates of $20B in Pt group metals, but it orbits to the outer edge of the Main Belt. (7474) 1992 TC, 4660 Nereus, and 65803 Didymos cross from near Earth to Mars, and so are interesting also as proto-Mars missions. The proposed repeatable trajectories and logistics from the Lagrange Points (FIGURE 3) to the M-type NEAs have the potential to become "revolutionary technologies."

C. Past Missions

The RAP team began our work with a review of all previous missions to asteroids or to fly by them. TABLE 1 shows a list of asteroids visited by Earth-launched spacecraft to date. Out of the hundreds of thousands of known asteroids, Earth's spacecraft have visited only twelve and we managed to "land" on only two. Obviously, there are thousands more asteroids to visit, many of them offering potential value for prospecting and mining – a veritable tabula rasa for exploration. TABLE 1 also shows mission cost (if available) and science returned. It shows that compared to other classes of mission, such as a Moon or Mars Lander, the science return per dollar has been relatively low.

TABLE 1. Asteroids Visited by a Spacecraft (Zacny et al., 2013a)

Mission and Body visited	Agency, Launch Date	Mission Description (Relevant to small bodies)	Cost (If available)
International Asteroidary Explorer (ICE)	NASA, 1978	Carried an X-Ray spectrometer and a Gamma burst spectrometer. Flew through the tail of the comet Giacobini-Zinner, and observed Halley's Comet from afar.	$3 Million ops-only add-on to an existing mission.
Vega 1 and Vega 2	SAS, 1984	Gathered images of Halley's Comet after investigating Venus.	
Sakigake	ISAS, 1985	Carried instruments to measure plasma wave spectra, solar wind ions, and interplanetary magnetic fields. Made a flyby of Halley's Comet.	
Suisei	ISAS, 1985	Carried CCD UV imaging system and a solar wind instrument for a flyby of Halley's Comet.	
Giotto	ESA, 1985	Carried 10 instruments to explore Halley's Comet, and provided data despite taking damage. Went on to explore comet Grigg-Skjellerup as well.	

Mission and Body visited	Agency, Launch Date	Mission Description (Relevant to small bodies)	Cost (If available)
Galileo	NASA, 1989	Carried 10 instruments. Flew by 951 Gaspra and 243 Ida, discovered Ida's moon Dactyl, and witnessed fragments of the comet Shoemaker-Levy 9 crash into Jupiter.	$1.6 Billion
Near Earth Asteroid Rendezvous (NEAR) Shoemaker	NASA, 1996	Characterized asteroid Eros using imagers, spectrometers, a magnetometer, and a rangefinder. Although not originally planned to do so, NEAR-Shoemaker landed on Eros.	$220.5 Million
Deep Space 1	NASA, 1998	Carried technology experiments. Flew by asteroid 9969 Braille and comet 19P/Borrelly.	$152.3 Million
Stardust	NASA, 1999	Carried instruments for imaging and dust analysis. Flew by asteroid 5535 Anne Frank, comet Wild 2, and comet Tempel 1. Returned sample material from comet Wild 2.	$199.6 Million
Asteroid Nucleus Tour (CONTOUR)	NASA, 2002	Carried instruments for imaging, spectrometry, and dust analysis. Spacecraft was lost.	$135 Million
Hayabusa	ISAS, 2003	Landed on the asteroid Itokawa and returned samples to Earth.	$170 Million
Rosetta	ESA, 2004	Flew by asteroid 2867 Steins and 21 Lutetia. Mission plans to put a lander on comet 67P/Churyumov-Gerasimenko.	~$1.2 Billion
Deep Impact	NASA, 2005	Carried instruments for imaging and spectrometry. Hit the comet Tempel 1 with an impactor and observed the collision. Will continue to study asteroids and asteroids as the EPOXI mission.	$330 Million
Dawn	NASA, 2007	Carries an imager, spectrometer, and gamma ray and neutron detector. Currently observing the asteroid Vesta, plans to move on to the asteroid Ceres.	$446 Million
Hayabusa 2	JAXA, 2014 (planned)	Plans to create an artificial crater on asteroid 1999 JU3and return samples that have not been exposed to sunlight and solar winds.	$367 Million
OSIRIS-Rex	NASA, 2016 (planned)	Plans to study C-type asteroid 1999 RQ36 called Bennu, and bring >60 grams of surface sample back to Earth.	$750 Million

III. Space Infrastructure Development Framework

The economic premise of RAP is that humans will develop an infrastructure for living and working in space. In this century, this infrastructure will grow to support hundreds of people and eventually thousands of people across the Solar System. We composed a space infrastructure development framework to characterize the growth of this infrastructure both in time and in the number of people living continuously in space. These space settlers will create a demand for commodities processed and products manufactured in space. The earliest commodity for which we see this demand is water. Water exists on the Moon and in the asteroids. The Delta V to return water from an asteroid can often be less than the Delta V to enter and escape from the Moon's gravity well plus the small gravity field of an asteroid will allow the use of highly efficient low thrust propulsion systems that are not useable when launching material from the lunar surface. We believe that water from asteroids can present a comparative advantage over lunar water and an absolute advantage over water from the Earth. In addition, the space infrastructure development framework prepares to accommodate other asteroid products including structural metals (Al, Fe, Mn, Ni, Si, Ti), platinum group metals (PGM), regolith for radiation shielding, regolith to provide soil for agriculture, and scientific samples as a commodity item for education and industrial research. We are designing the RAP spacecraft to play a leading role in building this space infrastructure and supplying the people who will live within it.

TABLE 2 is arranged along the horizontal axis into progressive phases of 15 years over 60 years from 2010 to 2070. The 15-year increment is significant for several reasons.

First, it marks the nominal period necessary to develop a major human spaceflight program. The Space Station development program took 15 years from 1984 when President Reagan announced "Space Station Freedom" until 1999, when the Russian Space Agency launched the Zarya Service Module, the "Functional Base Block" of the International Space Station (ISS). The current Orion Multipurpose Crew Vehicle (MPCV) program began with President Bush's "Vision for Space Exploration" and Constellation Program in 2004 and now expects a first crewed flight in 2018 – a 14 year period, (assuming no schedule slips or budget decrements).

Second, 15 years constitutes the "half-life" of a standard NASA civil service career of 30 years until full retirement. This time phasing poses a significant lesson insofar as it is necessary to support and maintain a core complement of experienced civil service engineers and scientists to carry out a major development program. The continuity of this experience is vital to sustaining the agency's ability to develop new major crewed spacecraft, space stations, lunar and planetary habitats and bases.

This assertion is not an empty platitude. One example from the legacy of the Apollo Lunar program should suffice to explain how essential it is to continue the corporate memory and pass that knowledge from generation to generation – regardless of whether that corporate memory resides among government employees, major aerospace contractor personnel or "NewSpace" entrepreneurial startups.

3 Mining and Processing Technology

The RAP approach to prospecting, mining, and processing flows from the preceding TABLE 2 Space Infrastructure Development Framework. Our mining strategy takes the form of FIGURE 4 the Hierarchy of Resources and Markets. It lays out the tactical approach to each type of likely candidate resource and the corresponding markets on Earth and in space. The Hierarchy of Resources and Markets shows that in general, the resources obtainable from Asteroids can be divided into 4 broad categories: free water, bound water, metals, and regolith.

It is a standard practice for terrestrial mines to organize mining operations around the main mineral product, while collecting bonus revenues from 'byproducts' of lesser concentration. In a similar vein, we will not travel all the way to an asteroid to mine just one resource. But neither will we be able to develop a "universal mining toolkit" that can extract and process any and all ores that we find on an asteroid or anywhere else. We will need to match particular technologies to specific deposits in selected locations. How do we align target body, the type of deposit, the mining technology, and what are the market and the price? On the other hand, the technology to grab and return different types of asteroids will be similar.

We also need to change the way we think about valuable commodities, and recognize the influence of location on value. Value on Earth does not equate to the same relative value in space. A simple analogy is this: What's worth more to a person who is stranded in the middle of a desert: a gallon of water or an ounce of gold?

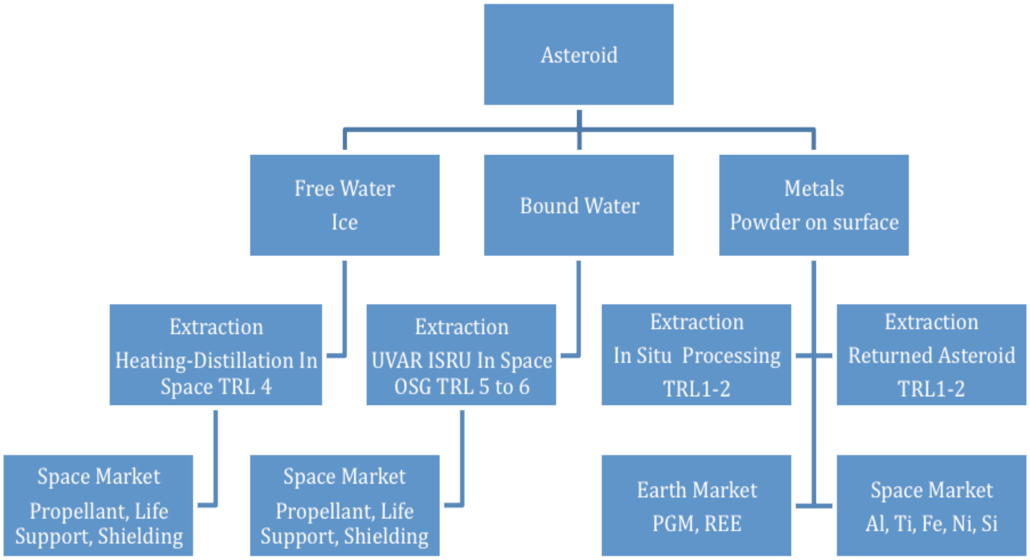

FIGURE 4. The Hierarchy of Space Resource Extraction and Markets.

TABLE 2. Space Infrastructure Framework

Metric	Recent		Near-Term		Intermediate-Term		Far-Term		Very Far-Term	
1. Milestone Year (Approx.)	2010		2025		2040		2055		2070	
2. 15 year Investment 2013 $B in Deep Space Infrastructure			25		50		100		200	
3. Rate of Investment in NYBs* at Milestone Yr	0		0.2		0.4		0.8		1.6	
4. People Living Continuously in Space	6		12-18		24-81		48-820		96-21,012	
5. Where Consumed	Space	Earth	Space	Earth	Space	Earth	Space	Earth	Space	Earth
6. Target ROI			TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Commodity 1	Water		Water	PGM	Water	PGM	Water	PGM	Water	PGM
Commodity 2			Rad Shielding	Science Samples	Rad Shielding	Science Samples	Rad Shielding	Science Samples	Rad Shielding	Science Samples
Commodity 3					Structural Materials		Structural Materials		Structural Materials	
Commodity 4					Life Support		Life Support		Life Support	
Commodity 5					Regolith for Soil		Regolith for Soil		Regolith for Soil	

NYB = NASA Yearly Budgets =~$17B in FY 2013

A. Mining Functions

Mining of all types must generally follow these steps: prospecting, excavating/mining, processing (e.g. comminution), extraction, and storage. Comminution is an energy intensive step and hence it should be avoided by mining pulverized regolith instead of small rocks or boulders. TABLE 3.1 explicates these steps.

Free water and bound water would be used in the space environment for life support, radiation protection, and propellant either as electrolyzed LOX/LH2 or as liquid water for Solar Thermal Propulsion). Based on the RAP teams work during Phase 1, the extraction and processing technology associated with this frozen water falls at of TRL 4 component or subsystem laboratory test. .

Metals may be used in space to make structural components for spacecraft and spacecraft subsystems, or brought back to Earth and sold. The most ready-to-hand approach would be to extract regolith dust or powder, feed it into a 3D printer, and then sinter it into various components for spacecraft (e.g. fuel tanks), structures (e.g. trusses), and habitats. Eventually, the technology will evolve to where it is possible to manufacture pressure vessel primary structure that is equal to aluminum, steel, or titanium counterparts made on Earth. The technologies necessary to mine minerals or metals, to extract metals from minerals, to de-alloy metals (from M-type asteroids), or to mine regolith and sinter it, are all at very low TRL. The cost to develop such technologies is not currently known (this topic is dealt with in detail further in this section). However, we believe that initially, low-hanging fruit could be pursued to establish a sustainable market. That low-hanging fruit is water.

Extracting free water is relatively easy – water ice can be sublimed and captured on a cold finger. Water extraction from hydrous minerals requires more heat, and so is relatively easy to achieve. In addition, methods of recovering of bound water from lunar regolith have been developed. Some of these methods could also be applicable to asteroids.

B. Water Extraction Tests

FIGURE 5 shows vacuum chamber tests to extract frozen water that the RAP team conducted at Honeybee Robotics (Zacny et al., 2012). These tests used analog simulants with various water fractions to demonstrate that water extraction efficiency can be as high as 90% at 80% energy efficiency (i.e. energy used relative to the energy required to heat up ice and sublime water vapor). FIGURE 5 shows the general experimental setup while FIGURE 6 shows results.

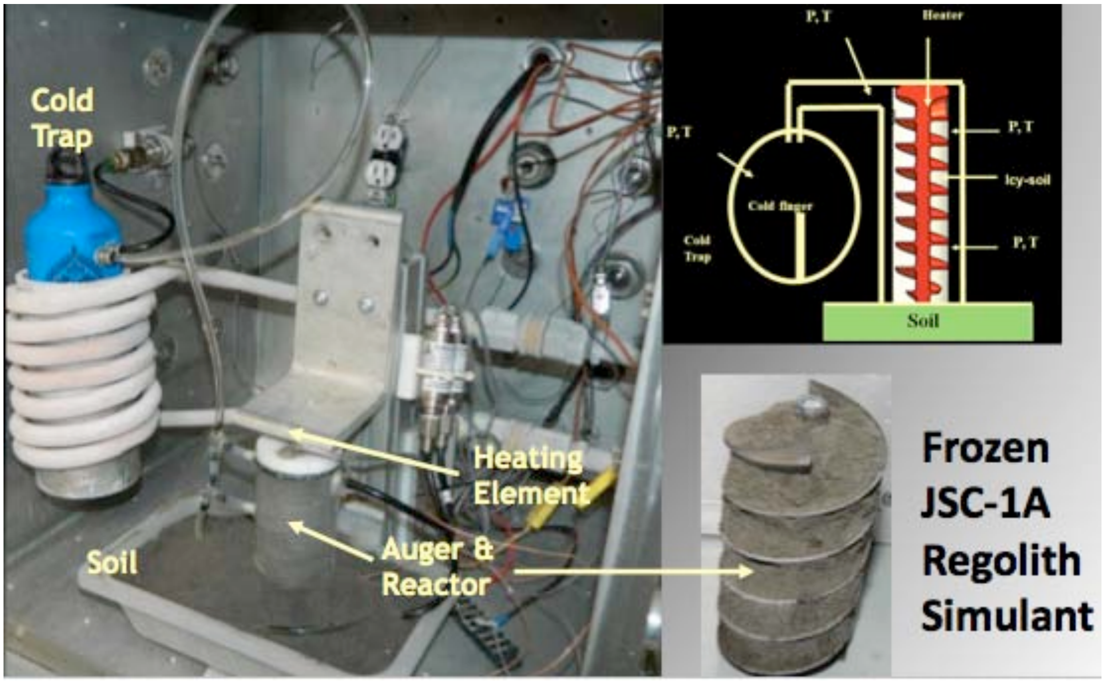

FIGURE 5. The laboratory set up for the Frozen Regolith Extraction experiment.

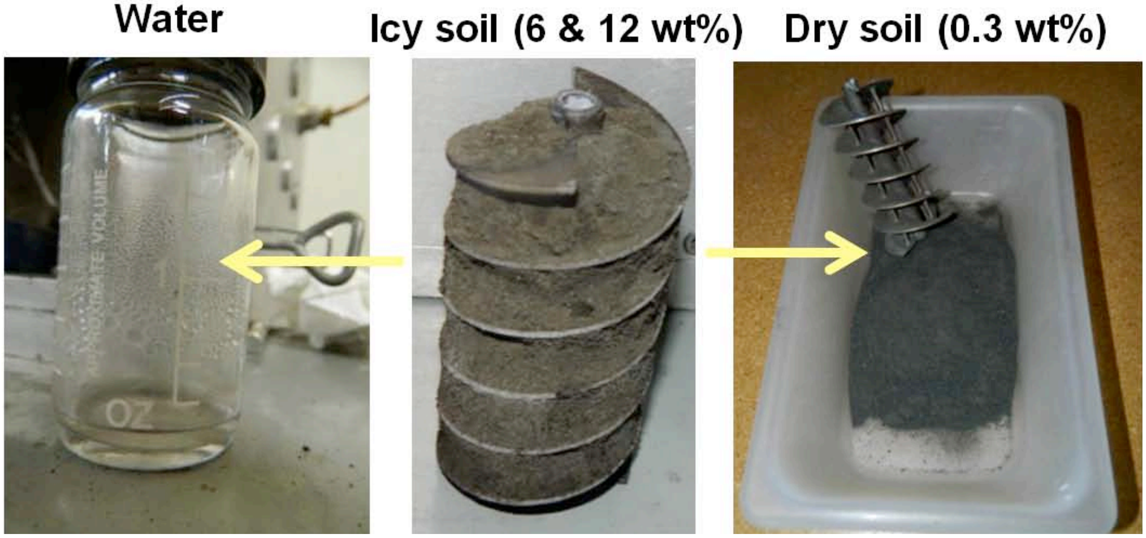

FIGURE 6. Water extraction process showing the auger and separation of liquid water and solid debris.

IV. Mission Design

For any interplanetary mission the orbital position of the departure and destination objects drives the energy cost of the mission. Having selected a destination there is little flexibility in selecting a departure time. Moreover, the time between mission opportunities is driven by their synodic period, which can be extremely long, i.e. decades or longer, for objects with similar orbit periods. Therefore, the RAP mission architecture encompasses a highly flexible approach to defining mission opportunities that makes uses of multi-body gravity assists, multi-revolution interplanetary transfers and deep space maneuvers to maximize the number of mission opportunities while minimizing total mission Delta V.

An important part of this approach is the use of an EML point as a staging point for departing and returning mining spacecraft. This gateway approach provides significant reductions in Delta V when compared to missions departing from or returning to LEO. This benefit accrues because the EML points are located at the edge of the Earth's gravity well; a vehicle there is only loosely tied to the Earth. This strategy reduces substantially the propellant required for those missions.

The focus of the Mission Design activities for RAP is to devise a mission architecture that can profitably return asteroid material to Cis-Lunar space. To meet this goal, the mission and spacecraft must be scalable to a variety of mission ΔV budgets, mission durations and cargo mass requirements. The system design must be resilient against performance shortfalls in the propulsion system and other spacecraft subsystems. The system must also reduce the total time required for any individual asteroid mining/recovery mission so that 'cost of money' impacts can be minimized.

Innovative mission design will prove crucial to achieving the above goals and conducting a successful asteroid mining enterprise. To achieve this transformational mission design, it will be necessary to challenge many of the familiar assumptions about staging, trajectory design, and the roles of spacecraft design and propulsion technology. The Mission Design consists of several elements including the Concept of Operations (ConOps), the trajectory, and ΔV budget.

One of the challenges of doing Mission Design for asteroid mining missions is that there exist a large number of potential destinations; each comes with its own ΔV budget and launch/arrival space. A mission design for a specific object will define what is needed for that mission to that specific asteroid but it will not answer the more general question of accessibility of other asteroids. Given the limited time and budget available for the RAP study we judged it impractical to make a survey of all potential asteroid mining missions. Instead, we developed a basic Delta V budget, based upon previous analyses of missions to Near Earth Asteroids. Next, we developed a spacecraft design that would allow us to tailor the performance of the mining spacecraft easily for each specific mission. By conceptualizing a system whose performance can grow as needed, we designed a spacecraft that can accommodate many – if not most – of the early asteroid mining missions that we might fly. This Robotic Asteroid Prospector (RAP) spacecraft will be capable of further growth for more challenging missions later.

A. Mission Design Drivers

The three major drivers on the asteroid mining mission architecture are:

- The type of propulsion system used for the Interplanetary Vehicle (IPV) –
    - Low thrust electrical,
    - High thrust chemical,
    - Solar thermal, or
    - A hybrid combining high and low thrust systems.
- The Earth-Moon orbital location from where the vehicle departs and returns.
- The source of the propellants for the IPV.

B. Selection of Propulsion System

Chemical propulsion offers the virtue of simplicity and a long experience base. However it suffers from low performance compared to electric propulsion. The best performing chemical propellant combinations require the ability to store cryogenic propellants for extended durations.

Electric propulsion offers specific impulse values an order of magnitude higher than chemical propulsion but at the cost of low thrust and the need for a large electrical power supply. However, this "cost" becomes a virtue for a mining mission since that large solar-electrical power system can also support energy intensive mining operations. The low thrust of an electrical propulsion system can require significant increases in mission duration as a result of the long time that the vehicle must spend spiraling out from Low Earth Orbit (LEO) prior to escaping from the Earth. We can reduce this problem by staging the mission from an EML point. However, the low thrust of a Solar

Electric system significantly increases the ΔV needed for the mission, which erodes some of the benefits available from such a system. Unfortunately the best propellants for use in a Solar-Electric propulsion system are not likely to be easily available from the asteroids and thus all of the propellant required for returning asteroid material to Cis-Lunar space will have to be carried out to the asteroid from the Earth.

However, using Solar Thermal, we can solve this problem by using water extracted from asteroids as the propellant for the return leg of the mission. A Solar Thermal propulsion system uses mirrors to concentrate solar energy that is then focused on a heat exchanger that is used to convert a liquid propellant to a high temperature gas that is then expelled from the vehicle generating thrust. The Isp available from this system is driven by the maximum temperature at which the heat exchanger can operate as well as the mean molecular weight of the propellant. If liquid hydrogen were used as a working fluid then the Isp would be comparable to that which can be achieved using a Nuclear Thermal Propulsion system. If plain water is used the Isp will be comparable to that of a moderate performance chemical propellant but this avoid the need to store cryogenic hydrogen and allows the use of water from an asteroid as a propellant without requiring that the water be broken into hydrogen and oxygen and the hydrogen being liquefied. Since this propulsion system allows the spacecraft to get as much propellant as is required for the return leg of the mission from the asteroid it will allow a great deal of flexibility in design of asteroid mining missions while minimizing the mass that has to be launched from the EML staging base to accomplish the mission. Additionally, the heat from the solar concentrators can be used for process heat to support mining operations at the asteroid and could also be used in a solar dynamic electrical power system. This later use would be important if a mining technology needed large amounts of electrical power, as opposed to process heat, but the extra cost and weight of the solar dynamic power system components cannot be justified for the normal levels of power needed for spacecraft operations. The enhanced mission flexibility, multiple uses for the solar concentrators and reduced departure mass makes Solar Thermal Propulsion the preferred option for our asteroid mining missions.

C. Lagrange Point Departure Benefits

The benefits of operating from a Lagrange Point using in-space propellants are:

- Operations from a Lagrange point will require significantly less ΔV than operations from LEO, and
- The cost of delivering propellant to that staging location will be lower than the cost of providing the propellants for operations in LEO.
- Therefore, an asteroid mission staged from a Lagrange Point using propellants derived from in-space sources will be significantly less expensive than an equivalent missions staged from LEO using terrestrially derived propellants.

D. Earth Departure Options

FIGURE 7 shows a schematic illustration for several options for departing from cis-lunar space and Figure 8 shows the Delta V required for various departure options.

The direct departure from LEO is the most straightforward since it is the departure mode that every interplanetary spacecraft launched to date has used. The direct departure from EML-1 is similar but with the lower ΔV requirement. At the appropriate time, the spacecraft makes a propulsive maneuver that increases its velocity and places it on a hyperbolic orbit. The timing of this departure is chosen so that the asymptote of the outbound hyperbola is aligned with the heliocentric velocity vector of the desired interplanetary orbit.

The Earth Swing-by option is similar to the Direct Departure but this approach has the spacecraft make a small maneuver at the EML point that puts it on an Earth approaching trajectory and then the powered departure maneuver is performed when the spacecraft is passing through the periapsis of its Earth flyby trajectory. By doing the departure maneuver when the spacecraft is moving at its highest speed the efficiency of the maneuver is maximized and the propellant needed for the departure maneuver is reduced significantly.

Additional benefits can be achieved by placing the spacecraft into a pre-departure phasing orbit prior to initiating the Earth flyby maneuver. This will allow a great deal of flexibility in the departure time while retaining the benefits of operations from an EML point and will allow us to achieve departure windows that are comparable to those which are traditionally used for interplanetary missions.

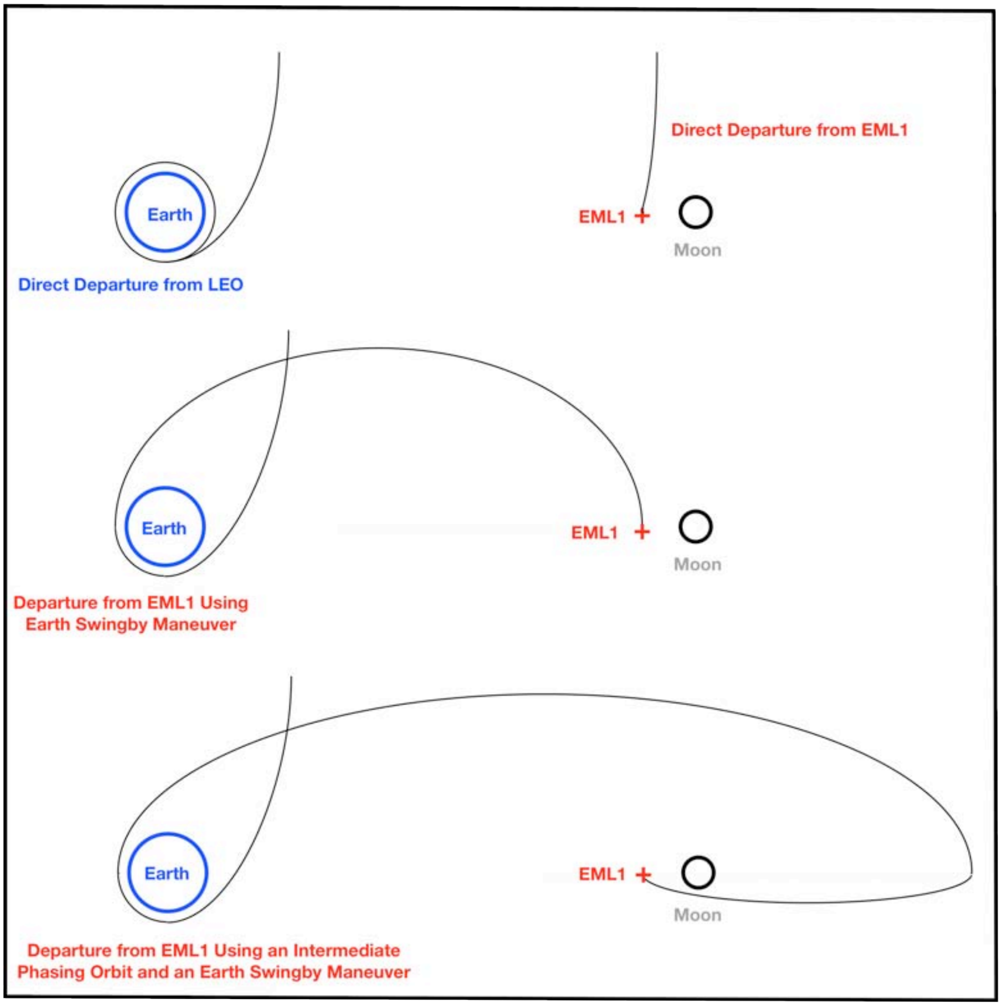

FIGURE 7. Schematic Illustration of Options for Departing Cis-Lunar Space

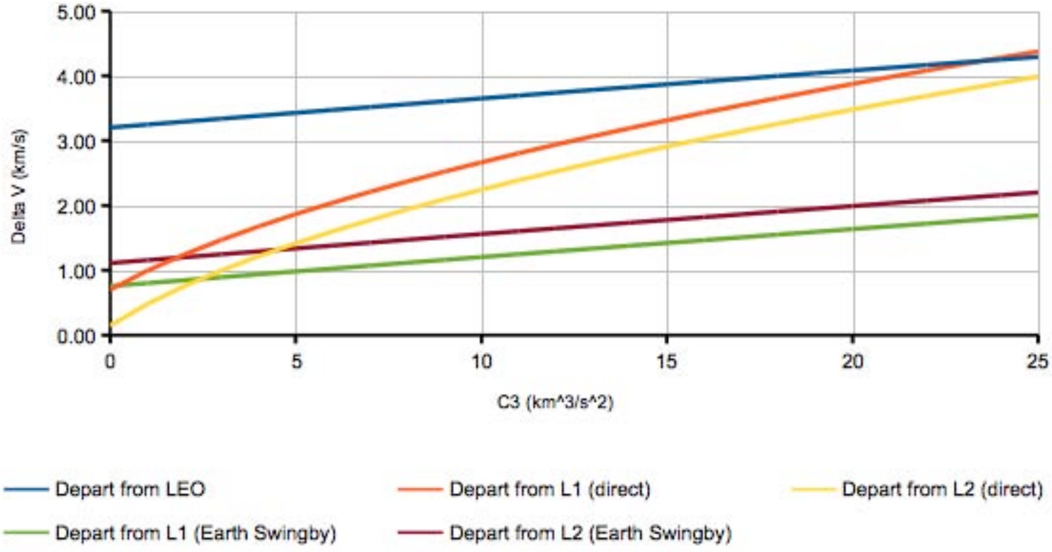

FIGURE 8. Comparison of Delta V Required for Various Departure Options

V. Spacecraft Design

The RAP team designed a prototype prospecting and mining spacecraft. Its key features are the implementation of a solar thermal propulsion (STP) system incorporating parabolic solar concentrators that can gather in excess of 1Mw of thermal energy when operating at a solar distance of 1 AU. The design of the RAP spacecraft enables use of this concentrated sunlight in two ways. First, it provides the heat at up to 2500K to the solar thermal engine to expand the fuel out the nozzle to create thrust. Second, it provides process heat to the on board mining, extraction, processing, and refining systems.

Water is the preferred fuel for the RAP STP system because it has several advantages when compared to conventional propellants. It is very dense when compared to its cryogenic by-products liquid oxygen (LOX) and liquid hydrogen (LH2). Not only does it not require the complexity and cost of electrolysis followed by cryo-cooling, but also the mass of the water tanks can be much smaller than the tankage required for a comparable mass of LOX and LH2. Moreover water can be stored in flexible tanks that simplify the task of propellant management in zero gravity but which also can be launched into space in a collapsed state, which will reduce tremendously the size of the fairing needed for the launch vehicle. Water propellant confers a further advantage insofar as the RAP spacecraft can refuel itself while on a mission from certain asteroids, thereby reducing the propellant loading required at the outset of the mission.

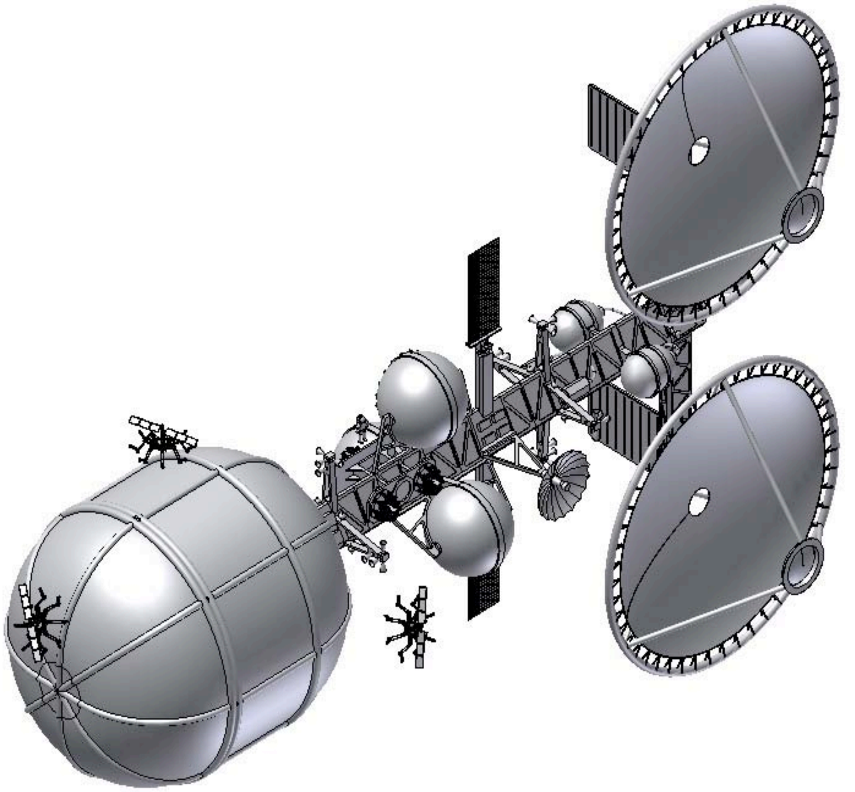

FIGURE 9. The Robotic Asteroid Prospector Spacecraft with the Containment Vessel in front in the Foreground and Robotic "Spiders" Maneuvering around it. At the Aft End Appear the Parabolic Solar Concentrators and the Two Water Propellant Tanks. Along the Truss in the Middle are the Three Payload Water Tanks, Quad Thrusters, Photovoltaics for Spacecraft Bus Power, and a Comm Antenna. (Zacny et al., 2013b)

Acknowledgments

The authors would like to acknowledge and thank the NASA Innovative and Advanced Concepts program for supporting this research.

References

ANSI/AIAA (2012). Guide to the Preparation of Operational Concept Documents, American National Standard, ANSI/AIAA G-043A-2012. Reston VA: American Institute of Aeronautics and Astronautics.

Beauford, R.E. (2011). “Rare Earth Elements: A key to understanding geological sorting processes in the solar system”, 27 April 2011, retrieved 1-10-13, http://rareearthelements.us/ree_in_space.

Binczewski, George J. (1995). The Point of a Monument: A History of the Aluminum Cap of the Washington Monument, Journal of Metals (JOM), 47 (11), pp. 20-25. http://www.tms.org/pubs/journals/jom/9511/binczewski-9511.html, retrieved 5 JAN 2013.

Brophy, et al.: Asteroid Retrieval Feasibility Study. Keck Institute for Space Studies, California Institute of Technology, Jet Propulsion Laboratory (2012), http://kiss.caltech.edu/study/asteroid/asteroid_final_report.pdf

Butler, J. (2012). “Platinum 2012”, Copyright Johnson Matthey PLC, retrieved on January 10, 2013, http://www.platinum.matthey.com/publications/pgm-market-reviews/archive/platinum-2012/.

Haskins, Cecilia, Ed (2010). Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities, INCOSE TP-2003-02-03.2. San Diego CA: International Council on System Engineering.

International Aluminum Institute (2013). World Aluminum Data, http://www.world-aluminium.org/statistics/alumina-production/#data, retrieved 5 JAN 2013.

Lewis, John S. (1997). Mining the Sky, Boston MA: Addison-Wesley Publishing Co.

Long, K.R.; Van Gosen, B.S.; Foley, N.K., and Cordier, D., (2010). “The principal rare earth elements deposits of the United States—A summary of domestic deposits and a global perspective: U.S. Geological Survey Scientific Investigations Report – 2010” Available at http://pubs.usgs.gov/sir/2010/5220/.

Mariano, A.N.; Cox, C.A.; and Hedrick, J.B.; (2010). "Economic Evaluation of REE and Y Mineral Deposits," Presentation at the 2010 Annual Meeting of the Society for Mining, Metallurgy & Exploration [SME], Phoenix, Arizona, available at http://www.smenet.org/rareEarthsProject/SME_2010_Mariano.pdf, 33 p.

NASA (2011). Apollo 17, http://www.nasa.gov/mission_pages/apollo/missions/apollo17.html

Norton, O. Richard (2002). The Cambridge Encyclopedia of Meteorites. Cambridge: Cambridge University Press. pp. 121–124. ISBN 0-521-62143-7.

Walters, A.; Lusty, P.; Chetwyn, C.; and Hill, A., (2010). “Rare Earth elements: Commodity profile”, British Geological Survey. Available online at www.mineralsuk.com.

Wikipedia (2013) Apollo 17, http://en.wikipedia.org/wiki/Apollo_17, retrieved 15 June 2013.

Zacny, Kris; Chu, Phil; Avanesyan, Arshak; Osborne, Lars; Paulsen, Gale; Craft, Jack; Oryshchyn, Lara A.; Sanders, Gerald B., Mobile In-Situ Water Extractor for Mars, Moon, and Asteroids In Situ Resource Utilization, AIAA Space 2012, 11-13 September 2012, Pasadena, CA

Zacny, K., P. Chu, G. Paulsen, M. Hedlund, B. Mellerowicz, S. Indyk, J. Spring, A. Parness, D. Wegel, R. Mueller, D. Levitt, (2013a), “Asteroids: Anchoring and Sample Acquisition Approaches in Support of Science, Exploration, and In Situ Resource Utilization”, Chapter 11 in Asteroids: Prospective Energy and Material Resources, Badescu (ed), Springer, to be published in 2013

Zacny, K., P. Chu, J. Craft, M. Cohen, W. James, B. Hilscher, (2013b), Asteroid Mining, AIAA Space2013, San Diego, CA, 10-12 Sept, 2013