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Asteroid Retrieval Mission Concept – Trailblazing Our Future in Space and Helping to Protect Us from Earth Impactors

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Abstract

The Asteroid Retrieval Mission (ARM) is a robotic mission concept with the goal of returning a small (~7 m diameter) near-Earth asteroid (NEA), or part of a large NEA, to a safe, stable orbit in cislunar space using a 50 kW-class solar electric propulsion (SEP) robotic spacecraft (~40 kW available to the electric propulsion system) and currently available technologies. The mass of the asteroidal material returned from this mission is anticipated to be up to 1,000 metric tons, depending on the orbit of the target NEA and the thrust-to-weight and control authority of the SEP spacecraft. Even larger masses could be returned in the future as technological capability and operational experience improve. The use of high-power solar electric propulsion is the key enabling technology for this mission concept, and is beneficial or enabling for a variety of space missions and architectures where high-efficiency, low-thrust transfers are applicable. Many of the ARM operations and technologies could also be applicable to, or help inform, planetary defense efforts. These include the operational approaches and systems associated with the NEA approach, rendezvous, and station-keeping mission phases utilizing a low-thrust, high-power SEP spacecraft, along with interacting with, capturing, maneuvering, and processing the massive amounts of material associated with this mission. Additionally, the processed materials themselves (e.g., high-specific impulse chemical propellants) could potentially be used for planetary defense efforts. Finally, a ubiquitous asteroid retrieval and resource extraction infrastructure could provide the foundation of an “on call” planetary defense system, where a SEP fleet capable of propelling large masses could deliver payloads to deflect or disrupt a confirmed impactor in an efficient and timely manner.

Keywords: *asteroid capture and retrieval, solar electric propulsion, space resources, in-situ resource utilization, human spaceflight, planetary defense*

1. Background and Introduction

The idea of utilizing asteroidal resources can trace its origins to long before humanity’s modern space age. In 1903, Konstantin Tsiolkovskii included the concept of using asteroids for resources in his most famous publication, *The Exploration of Cosmic Space by Means of Reaction Motors*. In 1977, Dr. Brian O’Leary, a former National Aeronautics and Space Administration (NASA) Astronaut Group 6 candidate and Asteroidal Resources Group team leader during the 1977 NASA Ames Summer Study on Space Settlements, proposed using mass drivers to move Earth-approaching Apollo and Amor asteroids to Earth’s vicinity at opportunities of low velocity increment (ΔV) [1]. Dr. O’Leary stated in the 1977 issue of the magazine *Science*, “It will be only a matter of time before asteroids will be discovered for which the energy transfer requirements for a mission are lower than for travel to the lunar surface. The scientific and prospecting motivations argue strongly for a step-up in the search program and in the follow-up work of orbital determination, compositional classification, and mission analysis.” [2] Currently, there are hundreds of candidate near-Earth asteroids (NEAs) requiring less energy than a mission to the lunar surface, yet the vast majority of these remain poorly characterized. More recently, Dr. John S. Lewis detailed how we can extract the vast resources available from our solar system in his

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influential book *Mining the Sky: Untold Riches from the Asteroids, Comets, and Planets*, published in 1997 [3]. Asteroid and comet mining has long been confined to the realm of science fiction, but today the technologies are available to begin transforming this endeavor from fiction into reality.

In late 2011 and early 2012, the feasibility of returning a small (~7 m diameter) near-Earth asteroid (NEA), or part of a large NEA, to cislunar space using a 50 kW-class solar electric propulsion (SEP) robotic spacecraft (~40 kW available to the electric propulsion system) and currently available technologies, was investigated by a team of engineers and scientists during two workshops at Caltech's Keck Institute for Space Studies (KISS). The KISS Asteroid Retrieval Mission (ARM) Study examined five general categories of benefits of returning an entire NEA, or alternatively part of a larger one, which included: 1) synergy with near-term human exploration; 2) expansion of international cooperation in space; 3) synergy with planetary defense; 4) exploitation of asteroid resources to the benefit of human exploration beyond the Earth-Moon system; and 5) public engagement [4]. The mission concept is continuing to be analyzed by NASA as a possible future mission opportunity. The ARM mission concept appears to be feasible, but it is important to carefully identify and assess key mission challenges in anticipation of future mission development activities.

Recent events on Earth have elevated the public's awareness of mining space resources and also highlighted the vulnerability of our planet and its inhabitants. First, two private companies announced their plans to mine asteroidal resources – Planetary Resources, Inc. in April of 2012 and Deep Space Industries in January of 2013. Shortly after the second public announcement, two nearly simultaneous, but unrelated asteroid events on February 15, 2013 made headlines around the world. While the world was anticipating the record close approach of the roughly 30-meter near-Earth asteroid 2012 DA₁₄ within 27,700 km of the Earth's surface, a smaller (approximately 17-20 m diameter), previously unknown asteroid entered the Earth's atmosphere over Russia and exploded at an altitude of approximately 23.3 km just southwest of the Russian city of Chelyabinsk about 16 hours earlier [5]. The shockwave from the airburst damaged buildings and injured over 1500 people on the ground, but no fatalities were reported. Finally, Comet C/2013 A1 (Siding Springs), a long-period comet (LPC) with a nucleus likely several kilometers in diameter, was discovered in January of 2013 and will make an extraordinarily close approach to Mars on October 19, 2014. Estimates, as of March 5, 2013, have the LPC passing to the surface of Mars at an altitude of only 50,000 km (approximately 2.5 times the distance of Mars' outermost satellite Deimos or less than twice the Earth close approach distance of 2012 DA₁₄), and there is currently a small chance that C/2013 A1 could impact Mars [6]. Recent estimates of the miss distance have increased somewhat, but this is particularly hard to predict since comets typically experience large non-gravitational forces (i.e., volatile outgassing) that significantly alter their orbits. The massive explosions resulting from 21 fragments of Comet Shoemaker-Levy 9 impacting Jupiter in July of 1994, along with these recent events, offer us timely reminders that we truly live in a "cosmic shooting gallery."

2. Mission Overview

The Asteroid Retrieval Mission concept assumes the use of a 50 kW-class SEP spacecraft accompanied by a suitable capture system to acquire and return a small (~7 m diameter) NEA, or part of a large NEA, to a safe, stable orbit in cislunar space using currently available technologies. The mass of the asteroidal material returned from this mission is anticipated to be up to 1,000 metric tons, depending on the orbit of the target NEA and the thrust-to-weight and control authority of the SEP spacecraft. The use of high-power solar electric propulsion is the key enabling technology for this mission concept, and is beneficial or enabling for a variety of space missions and architectures where high-efficiency, low-thrust transfers are applicable.

2.1 Spacecraft Configuration

The conceptual Asteroid Retrieval Mission spacecraft configuration depicted in Figure 1 includes a SEP spacecraft powered by two solar arrays (~50 kW beginning-of-life), which provide 40 kW of power to electric propulsion (EP) system with four 10-kW Hall thrusters using xenon (Xe) as the propellant and a specific impulse (I_{sp}) = 3000 s. Each solar array wing has a diameter of approximately 10 meters and a collection area of approximately 70 m². Each thruster has a dual-axis gimbal and a separate Power Processing Unit (PPU) and Xenon Flow Controller (XFC). The electric propulsion system produces approximately 1 N of thrust with four thrusters firing and is single fault tolerant with one spare thruster/gimbal/PPU/XFC string. Attitude control during SEP thrusting is provided by gimbaling the Hall thrusters. A separate Reaction Control System (RCS) consists of a single fault tolerant, hypergolic bipropellant subsystem containing approximately 900 kg of mono-methyl hydrazine (MMH) and nitrogen tetroxide (N₂O₄) with a gaseous nitrogen pressurization system, along with four pods of four thrusters, each with a nominal thrust of 200 N and an I_{sp} = 287 s. Recent trades have considered the use of a simpler, less expensive mono-prop hydrazine system with less propellant required. The RCS is primarily used to de-spin the captured asteroid and to supplement the electric propulsion system in

providing required attitude maneuvers during the mission. The fully fueled ARM spacecraft was estimated to be approximately 17,000 kg during the KISS ARM Study with 12,000 kg of xenon propellant [4], but was later sized to fill the 17,995 kg low-Earth orbit (LEO) lift capability of the Atlas V 551-class Expendable Launch Vehicle (ELV) during follow-on SEP performance analyses performed at NASA Langley Research Center (LaRC). A notional capture mechanism is depicted at the top of the spacecraft (the end opposite from the Hall thrusters) for illustrative purposes. A variety of capture mechanism approaches could be implemented, and a system with inflatable, deployable arms, a high-strength bag assembly, and cinching cables was proposed during the KISS ARM Study. A detailed discussion of all of the ARM spacecraft systems can be found in [4]. The spacecraft configuration and systems will be further refined as additional analyses and trades are conducted.

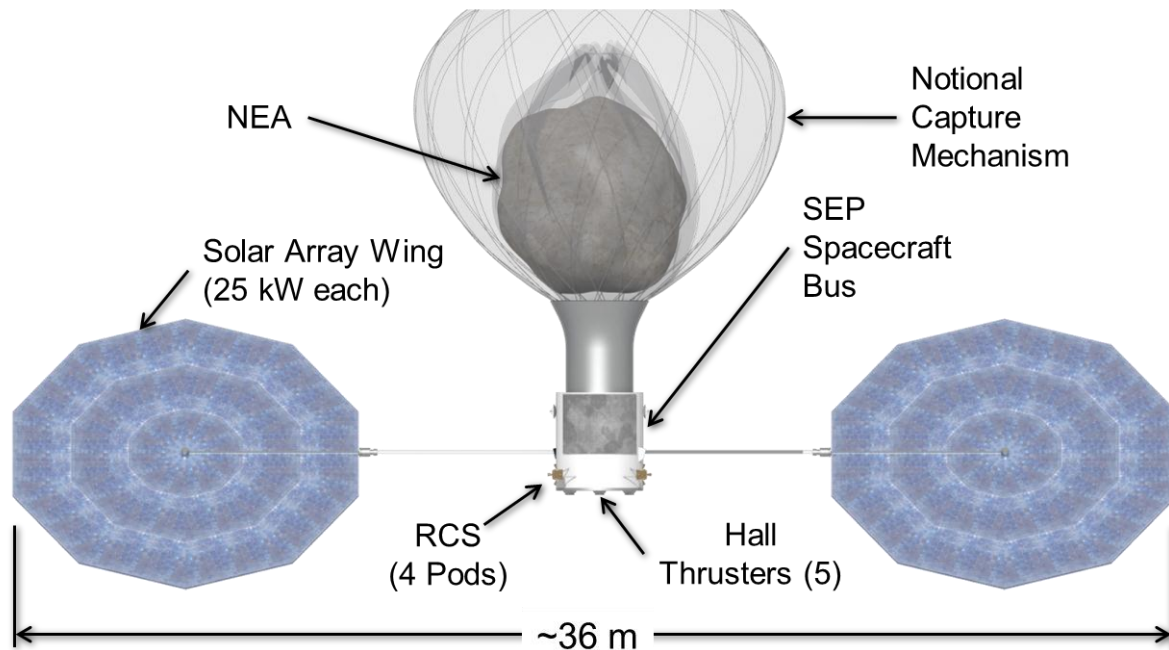


Figure 1: Asteroid Retrieval Mission (ARM) spacecraft configuration (image credit: NASA/AMA, Inc.).

2.2 Typical Mission Sequence

The ARM mission sequence is depicted in Figure 2 and has a total duration of typically 6-10 years, depending on the target's orbit and the mission constraints. The robotic mission begins with the launch of the ARM spacecraft to the delivery orbit on an Expendable Launch Vehicle (ELV). The selected delivery orbit depends on the NEA target, the overall mission time constraints, and the capability of the launch vehicle. The ARM spacecraft is either delivered to LEO and spirals out using the low-thrust SEP propulsion to a Lunar Gravity Assist (LGA) or is injected directly to LGA or the outbound trajectory by the launch vehicle. Approximately two additional years need to be added to the mission duration to provide sufficient time to spiral from LEO. The interplanetary cruise to the NEA can take many months to several years to complete. Operations at the asteroid are assumed to be accomplished in approximately 90 days and include: 1.) final target characterization; 2.) deployment of the capture mechanism; 3.) approach and proximity operations with the NEA; and 4.) capture, de-spin, and securing of the asteroidal material for the return leg of the mission. A notional capture mechanism with flexible ribs and two enclosure bags containing an entire small NEA or a boulder from a large NEA is depicted in Figure 1. Upon arrival into cislunar space, a second LGA maneuver is performed that places the ARM spacecraft with its asteroidal material into a safe, stable utilization/storage orbit. A variety of different final orbits can be considered, with lunar Distant Retrograde Orbits (DROs), which orbit ~60,000-70,000 km from the lunar surface, being desirable because of their long-term stability (greater than 100 years) and fairly low insertion ΔV requirements. However, the amount of additional propellant to insert into the utilization/storage orbit increases significantly as the asteroidal return mass becomes large. Performing an initial mission with a smaller mass can help increase the probability of mission success, with larger masses being returned in the future as technological capability and operational experience improve.

2.3 Solar Electric Propulsion is the Enabling Technology

Due to its high specific impulse, low-thrust solar electric propulsion is the key enabling technology for enabling the transfer of the large masses associated with moving asteroidal material through heliocentric space.

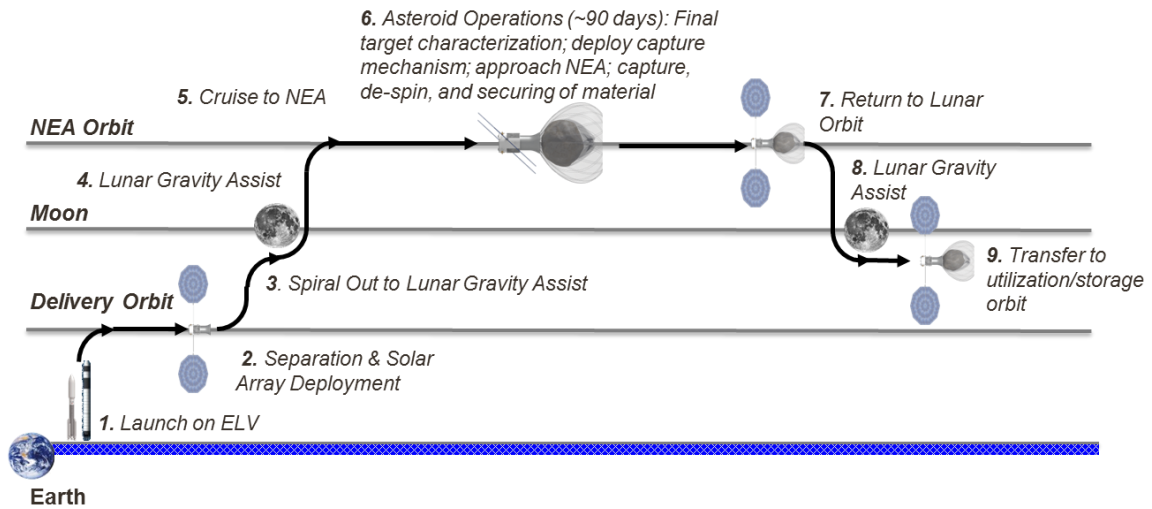


Figure 2: Typical ARM sequence (image credit: NASA/AMA, Inc.).

Figure 3 provides an example of the tremendous reduction in Initial Mass in Low-Earth Orbit (IMLEO) that can be achieved by utilizing SEP compared to chemical propulsion. Depicted is a comparison for returning 1,000 metric tons of asteroidal mass from an accessible Apollo NEA, such as 2008 HU₄ (semi-major axis (a) = 1.09 AU, eccentricity (e) = 0.073, and inclination (i) = 1.25 deg.). Compared to SEP using Xe propellant, over 20 times more IMLEO is required for a low-efficiency, space-storable propellant, such as nitrogen tetroxide (NTO) and mono-methyl hydrazine (MMH), and over 12 times more for a high-efficiency, liquid oxygen/liquid hydrogen (LOX/LH₂) propulsion assumed to have zero-boil-off (ZBO) cryogenic storage capability. This allows the mass of the fully fueled ARM spacecraft to be less than 20 t and be launched on a single ELV. SEP systems are beneficial or enabling for a variety of space missions and architectures where high-efficiency, low-thrust transfers are applicable. SEP has been successfully demonstrated on the current robotic Dawn spacecraft, which launched in September of 2007, visited the main belt asteroid Vesta in 2011-2012 and is currently planned to arrive at Ceres in early 2015. Other high efficiency propulsive techniques, such as mass drivers and solar sails, are potentially feasible for returning asteroids, but have significant technological hurdles to overcome. Mass drivers require extensive interaction with the asteroid and solar sails require extremely large, very light-weight flexible structures. In addition to technological and operational complexities, mass drivers provide momentum exchange by expelling mass from the asteroid itself, which has the potential to add unnecessary debris in the solar system, particularly in cislunar space. Mankind has been successful in creating a significant orbital debris problem in Earth orbit, and we should take prudent steps to not create similar problems as we venture into deep space.

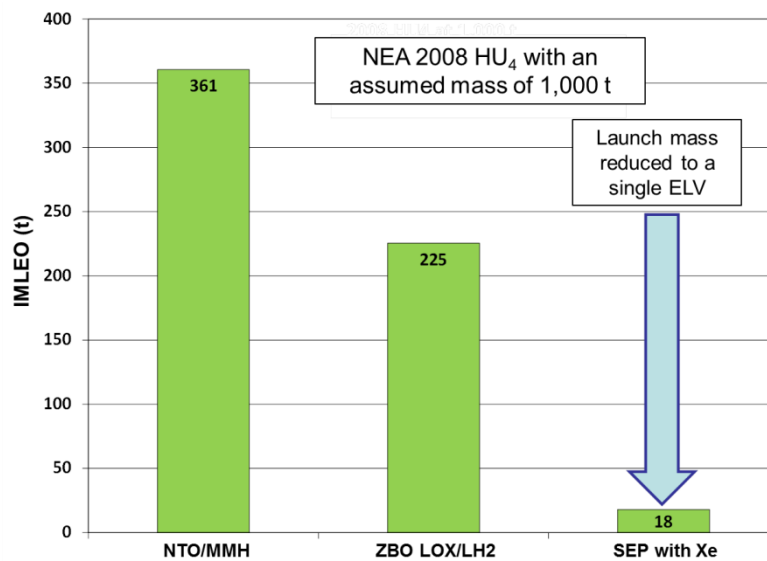


Figure 3: IMLEO (t) required for retrieving a 1,000 t NEA using different propulsion options.

2.4 Retrieval Options

There are three primary options for capturing and returning asteroidal material: 1.) retrieve an entire small NEA; 2.) retrieve part of a large NEA; and 3.) retrieve a NEA moonlet (secondary). Each of these options has advantages and disadvantages, but the single most significant risk for all of them is insufficient characterization of the target before the retrieval mission is developed, and ultimately before the mission is initiated. If definitive characterization of the target NEA is received before the launch of the ARM spacecraft, or possibly before the spacecraft reaches LGA for scenarios that spiral out from LEO, it may be possible to redirect the mission to a secondary or future target if the primary target is deemed unacceptable. The main identified advantages and disadvantages are provided below along with the key issue for each option, which are all variants of the problem associated with insufficient characterization.

- **Retrieve an Entire Small NEA**
 - **Advantages:** Many targets (potentially millions); single, free-floating target may simplify capture operations; more likely to be coherent or monolithic.
 - **Disadvantages:** Lack of sufficiently characterized targets (including composition); large size/density uncertainty; likely high spin rate likely increases capture complexity.
 - **Key Issue:** Lack of comprehensive remote survey and characterization of small NEAs (~10 m diameter or less) increases mission risk if target is larger and/or more dense than anticipated.

- **Retrieve Part of a Large NEA**
 - **Advantages:** Flexibility to optimize return mass; better able to select a well-characterized target with desirable resources; likely low spin rate reduces rendezvous and proximity operations complexity; more synergistic with planetary defense (NEAs ~10 m or less are unlikely to pose a risk) and with human and science missions (large NEAs are likely more diverse).
 - **Disadvantages:** Have to capture material in presence of main body and confirm that material is detached/detachable from the main body; likely fewer targets with low ΔV for return.
 - **Key Issue:** Verification of presence of acceptable size rocks or recoverable material in all likelihood requires a precursor scout mission. Increased mission risk and/or complexity without verification.

- **Retrieve a NEA Moonlet (Secondary Body)**
 - **Advantages:** Single target; potential to be a “rubble pile” could simply processing of resources (if present in the regolith) or could assist in providing acceptable mass properties after capture.
 - **Disadvantages:** Currently, no known NEAs with sufficiently small moonlets; possible debris field; stability of main body after capture of secondary body; stability of body during capture.
 - **Key Issue:** Lack of comprehensive remote survey and characterization to identify NEAs with sufficiently small moonlets.

2.5 Capture System

There are many possible approaches for capturing asteroidal material, either an entire “free-flying” small NEA, a moonlet, or part of a large NEA, but most of the concepts fall into the following five general categories: 1.) grabbing; 2.) drawing; 3.) agitating; 4.) adhering; and 5.) lofting, or could combine two or more approaches. Grabbing mechanisms capture material by grasping or surrounding it. Drawing mechanisms pull material from the surface to the spacecraft. Agitating mechanisms interact with the surface to dislodge and collect the asteroidal material. Adhering concepts deploy a collector that allows the regolith to “stick” to it in some manner and then is returned to the spacecraft. Finally, a lofting mechanism gathers and/or lifts the material from the surface and aggregates it in some manner. Personnel at the Jet Propulsion Laboratory (JPL) are continuing to analyze the inflatable system proposed during the KISS ARM Study for capturing an entire small NEA, while personnel at LaRC are conceptualizing several mechanism concepts that could retrieve part of large NEA and also capture a single small NEA or moonlet.

For concepts that retrieve part of a large NEA, the addition of an end effector is advantageous for some approaches. The mechanism comprises the primary capture device and the end effector is typically a smaller component that is attached to the mechanism and facilitates the collection of material. Figure 4 provides some initial concept sketches of a few of the capture mechanisms being considered. Beginning at the bottom left and continuing clockwise: (1) a Long Reach Manipulator System (LRMS) with tendon actuated arms used to secure a bag around the asteroid; (2) a harpoon and tether system allows the ARM spacecraft to maintain a safe standoff distance; (3) composite flexible ribs to hold a bag open during capture with lanyards for cinching the bag and pulling in asteroid to a rigid mount on SEP; (4) the “Pac Man” approach that utilizes a rigid or expandable/inflatable shell that is split along the longitudinal plane to function as jaws to capture a small

NEA/moonlet, or scoop up a boulder and/or asteroidal regolith (deployable Hoberman hemi-spherical structure shown); (5) the inflatable ribs and bag concept from the KISS ARM Study with lanyards for cinching bag and securing the NEA. Four of the concepts shown employ a grabbing technique, while the second approach utilizes a drawing approach. Additional capture mechanism approaches are currently under study.

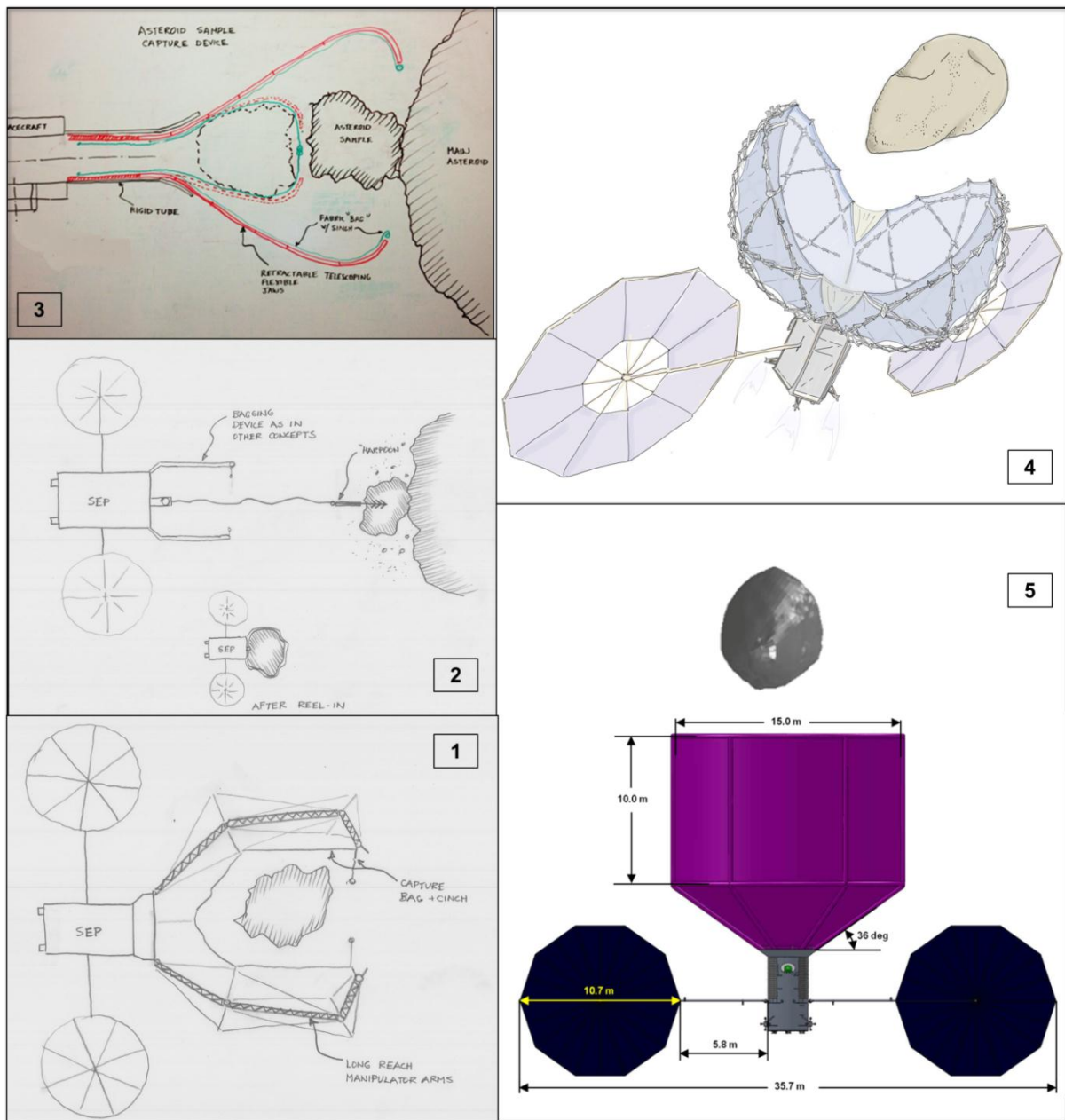


Figure 4: Conceptual capture mechanisms (image credits: NASA/AMA, Inc. and KISS).

2.6 Single vs. Separable Spacecraft

The ARM spacecraft shown in Figure 1 is a single spacecraft configuration. This configuration requires the entire SEP spacecraft to be sufficiently agile to match the asteroid rotation state, capture it, and de-spin the asteroid and the entire spacecraft. An alternative approach incorporates a separable spacecraft that splits the transit functions from the NEA rendezvous and proximity operations, capture, and de-spin functions. In this approach, the SEP spacecraft is responsible for transporting the capture spacecraft to the vicinity of the target, the post-capture rendezvous with the capture spacecraft and the NEA, and transporting the entire “stack” to cislunar space. The SEP spacecraft would include the electric propulsion system, the solar arrays, and the power management and distribution system. It would also have an articulated high-gain antenna for long-range communications with Earth, a short-range (omnidirectional) communications capability, Attitude Control System (ACS), Reaction Control System (RCS), and Command and Data Handling (C&DH). The capture

spacecraft would separate from the SEP stage, rendezvous with the target and then capture and de-spin the NEA or asteroidal material. Its systems would include an ACS, RCS, C&DH, short-range communications with the SEP spacecraft, and the capture mechanism and instruments for acquiring and securing the asteroidal material. This separable spacecraft configuration was not pursued during the KISS ARM Study primarily because it would likely be more expensive, but also because it would necessitate the need for autonomous rendezvous and docking with the SEP spacecraft in deep space and it would also have limited energy capability once it separates from the SEP. However, the advantages of being able to monitor the NEA capture and control operations, particularly for returning part of a large one, might outweigh the potential disadvantages.

3. Target Selection and Return Mass

Many candidate NEA targets have been identified that provide low ΔV mission opportunities, and initial return mass scans indicates multiple target opportunities exist within the capability of a 50 kW-class SEP spacecraft. However, the vast majority of possible ARM targets have not had their physical characteristics (size, spin rate/state, composition, etc.) sufficiently determined, or determined at all. This is particularly true for extremely small NEAs (approximately 5-10 meters in diameter), which the ARM spacecraft would be capable of retrieving. Only two large, stony (S-type) asteroids have been robotically visited – 433 Eros and 25143 Itokawa. As discussed in Section 2.4, the most significant technical risk for the ARM concept is lack of target characterization. Most aspects of the mission are tractable systems engineering problems. However, uncertainty in target characteristics requires significant margins to be included, which can lead to the over-engineering of the spacecraft systems to accommodate the uncertainties. In some cases, it is impractical to implement a system capable of accommodating the entire range of target uncertainties, which results in a certain amount of mission risk that must be accepted. Proper characterization of the target can dramatically reduce this mission risk. Two of the fundamental uncertainties are whether or not the material can be obtained by the capture mechanism and whether or not the mass is low enough to allow its return by the SEP spacecraft.

3.1 Size and Uncertainties

Our limited robotic visits to larger NEAs indicate that the presence of material ranging from dust to boulders should be common place. On asteroid 25143 Itokawa, which measures $535 \times 294 \times 209$ m [7], it is estimated that there are over 300 boulders 5-10 meters in diameter, and more recent estimates indicate more than double this estimate [8, 9]. Returning mass from a large NEA affords flexibility in the mass that can be returned, and targeting a NEA that has already been visited by a robotic precursor can verify that acceptable asteroidal material is available. Additionally, most large NEAs are slow rotators (typically once every few hours). They also reflect more sunlight, which makes it easier to remotely obtain spectral information inferring their composition and lightcurves to determine their spin rate, and possibly spin state. Finally, planetary radar facilities like the Arecibo Observatory in Puerto Rico and NASA's Goldstone Solar System Radar in California can more readily obtain sufficient signal-to-noise ratios for larger NEAs, greatly increasing our knowledge of the target's physical characteristics, including the target's shape, spin state, density, surface roughness, and the possible presence of moonlets. However, these radar systems have resolution errors that can be several meters depending on the return signal from the target. Therefore, a robotic precursor to the target may be required to obtain sufficient observational data to assure the presence of returnable material.

The estimated size of a NEA can vary by nearly 450% based on a visual albedo (P_v) between 0.03-0.60, which is well within the range of possible values (some NEAs reflect less than 3% of the incident sunlight and some reflect more than 60%). This translates into a volume that could vary by almost a factor of 90. Uncertainties in the object's density could add an additional uncertainty factor of three or more to the NEA's mass. For example, a target NEA with an absolute magnitude (H) of 28.0 could be as small as 4.4 meters in diameter with an albedo of 0.60, or as large as 19.5 meters with an albedo of 0.03 (assuming a spherical body). Assuming the same density of 3 g/cm^3 , the 4.4 meter NEA would have a mass of 134 t, while the 19.5 meter NEA would have a mass of 11,647 t. A highly capable Near-Earth Object (NEO) survey and characterization program is critical to reducing the uncertainties associated with the size and mass of smaller asteroids.

Our understanding of very small NEAs (up to 10 m) is extremely limited at this time. Many small NEAs are fast spinners, some rotating faster than once per minute. The physical characteristics of these objects are very difficult to study remotely. With sufficiently accurate observations, it is possible to discern how a NEA's orbital motion differs from an orbit due purely to modeled gravitational forces and estimate the object's Area-to-Mass Ratio (AMR). With a credible AMR estimate, some constraints can be placed on the upper and lower bounds of the NEA's mass. However, these estimates still include assumptions about the object's visual albedo, which can still be quite large, as well as the shape of the object. Accurately characterizing small NEAs remotely is extremely difficult, and a robotic precursor may still be needed to assure the target's acceptability.

3.2 Target Type

The type of asteroid selected as the target is a critical decision. There are many motivations for and benefits of this mission concept, which are discussed in Section 4, but the authors maintain that the primary motivation for retrieving large quantities of asteroidal material should be to help enable the utilization of space-based resources, through the development of technologies and operational techniques, that foster the creation of a viable, sustainable space-based economy. For some targets, the recoverable materials might be extracted at the object's natural location in heliocentric space. For other targets, where the percentage of recoverable materials is high, it may be more practical to return the raw asteroidal materials to a processing and manufacturing site at an advantageous location, such as cislunar space. Other factors, such as the reliability of the processing and manufacturing equipment, operating and servicing the equipment, and power availability, will ultimately influence these decisions. When an operational fleet of retrieval spacecraft and processing facilities has become a reality, various types of asteroidal and cometary material can routinely be harvested from our solar system. However, initially the targets with the highest potential for useful resources that can be extracted with the least amount of effort should be selected.

At the top of this list are carbonaceous (C-type) NEAs, which could provide vast quantities of water-rich material for resource extraction. C-type NEAs with hydrated minerals can consist of up to 40% extractable volatiles by mass (~20% water and ~20% carbon-bearing compounds) [3]. These objects are typically very dark (3-10% albedo) and difficult to detect, particularly with ground-based telescopes operating in the visible spectrum. Carbonaceous asteroids possess low compressive strength, which simplifies cutting, crushing, and processing, and are believed to comprise a significant percentage of the NEA population. Observational biases likely result in their population being significantly underestimated. Due to their friable (crumbly) nature, less than 5% of the recovered meteoritic falls are carbonaceous meteorites [10]. The concentrations of volatiles in a carbonaceous NEA could be up to ~2,000 times greater than solar-wind-implanted volatiles in lunar regolith (outside of permanently shadowed cold traps). Additionally, carbonaceous asteroids have concentrations of many metals, particularly iron and nickel, aromatic hydrocarbons, and various minerals. For example, reaction of organic carbon with magnetite during volatile extraction results in metallic iron at concentrations ~300 times greater than lunar regolith. It is worth noting that the presence of free iron in lunar regolith is from asteroid and comet impacts on the Moon. It is anticipated that ~60% of carbonaceous asteroid could be processed into useful resources and that the remaining metal-free silicate "slag" would be similar to lunar surface material [3]. Figure 5 is a photograph of a 723 gram fragment of the friable Murchison CM2 carbonaceous chondrite meteorite that fell near Murchison, Victoria, Australia on September 28, 1969, after the parent body broke up in flight and spread fragments over a five square mile area. It represents the type of high-value asteroidal material that can be harvested from NEAs. The Murchison meteorite also contains amino acids such as glycine, alanine and glutamic acid, showing that, in addition to their resources, these objects also have a tremendous scientific value in the study of the formation of the solar system and the origin of life.



Figure 5: Murchison CM2 carbonaceous chondrite meteorite – 723 gram fragment (photo credit: Jim Strope).

3.3 Return Mass Capability

While there is great deal of uncertainty with respect to the composition, size, mass and rotational characteristics of the NEA population, the orbital elements of known NEAs can be used to estimate the return mass capability for the SEP spacecraft and mission sequence described in Section 2. The return mass for a particular NEA is dominated by the inbound heliocentric and cislunar capture ΔV requirements, and return mass estimates for various SEP configurations and launch vehicle options were calculated. As an example of the return capability provided by the SEP spacecraft, Figure 6 illustrates the returnable mass in metric tons as a function of the outbound and inbound ΔV (including capture into a stable lunar orbit) for a SEP spacecraft with 40 kW of power available to the EP system, an $I_{sp} = 3000$ s, and launched to LEO on an Atlas V 551 ELV.

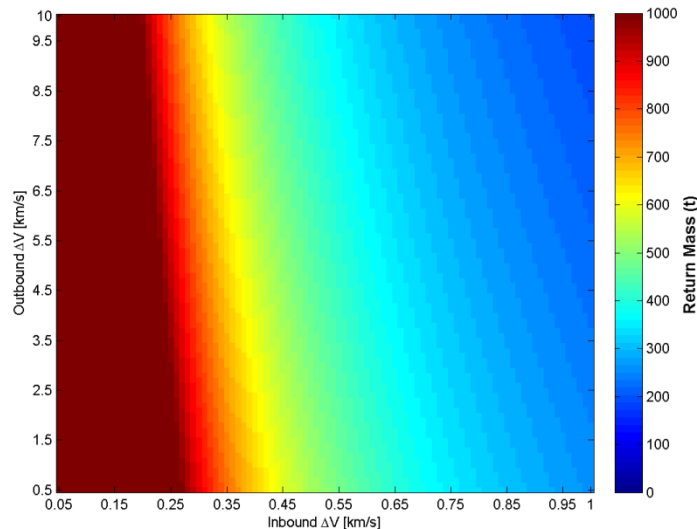


Figure 6: Return mass (t) vs. outbound and inbound ΔV : 40 kW EP system, $I_{sp} = 3000$ s, and Atlas V 551 ELV.

A multi-revolution heliocentric Lambert scan algorithm was developed and used to estimate the return mass estimates for all known NEOs identified in the JPL Horizons Small-Body Database Search Engine [11], and assuming user specified dates for Earth departure (i.e., LGA) and return date to cislunar space. This initial scan assumes limits for LGA performance based on departure and arrival declinations and provides good estimates for Earth departure and return times, as well as return mass. For the 8,986 known NEOs in the JPL Horizons Small-Body Database as of July 30, 2012 and for Earth departure after the beginning of 2019 and return before the end of 2030, this initial Lambert scan identified the number of targets with the following estimated return mass ranges shown in Table 1. For the Lambert scan performed, Figure 7 shows the top 20 targets with their maximum return masses to cislunar space for three different launch vehicles and delivery orbits: 1.) Atlas V 551 delivery to LEO; 2.) Estimated Falcon Heavy delivery to geosynchronous transfer orbit (GTO); and 3.) Estimated Falcon Heavy delivery to translunar injection (TLI). The performance for the different options is generally close, but the combination of the ΔV requirements for a particular target and the constraints on system power and available propellant can change the performance. These high-thrust Lambert scans are only estimates of the actual low-thrust trajectory that will be used by the SEP spacecraft, and do not include the ΔV required to insert into the final utilization/storage orbit, which will reduce the returnable mass. Additional analyses are currently being performed to determine the error in the estimates. For the limited number of targets that been compared to date, the results agree quite closely. The typical difference in return mass is approximately 2-11% and the mission departure and arrival date can differ by a few days to a few months, with the stay time at the target generally less than the stay time predicted by the Lambert scan.

Table 1: Number of targets and range of return masses estimated by Lambert scan based on 8,986 known NEOs.

Return Mass (t)	Number of Targets
0-50	3,282
50-100	236
100-200	62
200-500	13
500-1,300	4
1,300-7,027	1

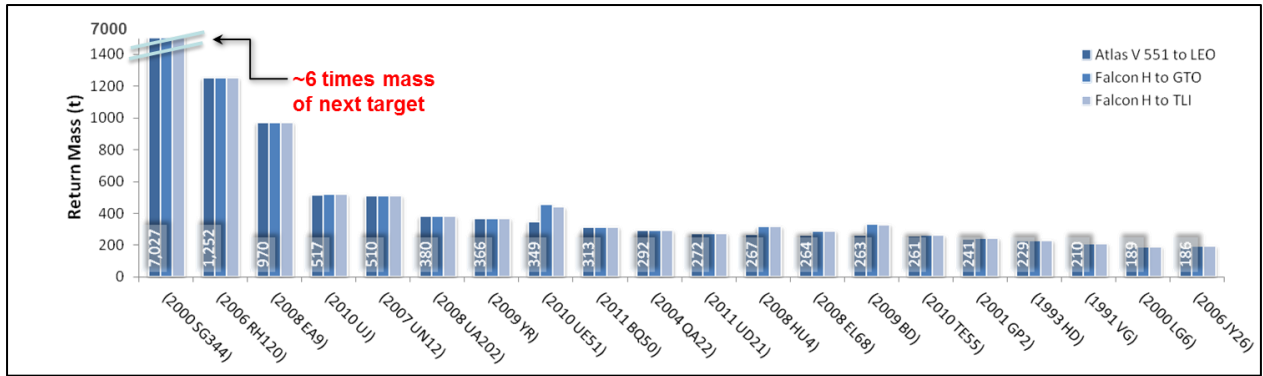


Figure 7: Top 20 return masses – departure on or after January 1, 2019 and return by December 31, 2030.

The physical characteristics of these and of the other 60 targets with estimated return masses of ~100 metric tons or greater are also generally not known and no remote or in-situ characterization is available. Among the top 20 targets, four are expected to have a minimum diameter (corresponding to a $P_v = 0.60$) estimated to be larger than the 7 m, and all 20 could have a maximum diameter (corresponding to a $P_v = 0.03$) larger than 7 m. The orbits of these objects have not been calculated with extreme precision, though a few have orbits that are known sufficiently to be able to conduct a SEP mission. A SEP spacecraft, with the aid of a deep-space camera, can make orbit adjustments much more efficiently than can a chemical propulsion system. One object, 2009 BD, has some preliminary AMR estimates and spin rate information that indicates that it may be a retrievable target, at least with respect to mass and diameter. If sufficient observational data can be obtained to constrain the mass, rotational characteristics, and composition of a small NEA like 2009 BD, a mission to return the entire target is possible.

It should be noted that 2000 SG₃₄₄ is a unique NEA target since its orbit makes it so accessible, and a 40 kW EP system can return approximately six times the mass (~7,000 t) compared to the next most accessible NEA (~1,300 t for 2006 RH₁₂₀) during this time period. Its physical characteristics are currently unknown, but a low-cost robotic precursor scout could be justified due to the extraordinary potential of 2000 SG₃₄₄ for resources, and the fact that it is by far the most accessible human mission target currently known in the 2020-2030 timeframe. The ARM could even pre-deploy destination systems for a human mission to 2000 SG₃₄₄, and the crew could participate in the acquisition of the returned material (teletotally or directly), which could increase the probability of mission success. If 2000 SG₃₄₄ is a low-albedo, C-type NEA, it could be up to ~86 m in diameter and have a mass of ~800,000 t, which in turn could contain ~160,000 t or more of water. This would be enough water to sustain future space exploration and settlement efforts for the foreseeable future. Finally, because of its favorable orbit ($a = 0.98$ AU, $e = 0.067$, and $i = 0.11$ deg) significant mass is returnable during much of its synodic period. Over 1,000 t could be returned from 2000 SG₃₄₄ to cislunar space by mid-2027.

3.4 Retrieving Material from a Targets with Planned or Proposed Robotic Missions

The issues associated with the lack of NEA characterization have discussed several times in this paper. If retrieval masses below ~50 t are deemed acceptable for an initial ARM, then characterization for several targets could be provided by planned or proposed robotic missions, which are all currently being sent to large carbonaceous (C-type or B-type) NEAs. These lower return masses would likely necessitate retrieving part of the target, since 50 t corresponds to an object that that is approximately three meters in diameter (assuming a spherical body with a density of 3 g/cm³). Currently, there are two planned robotic missions to large C-type NEAs, and a third that has been proposed. All three of these NEAs are estimated to be approximately 400 meters in diameter or larger. 1999 JU₃ is a Cg-Type Potentially Hazardous Asteroid (PHA) approximately one kilometer in diameter. A PHA is an NEA with an orbit that comes within 0.05 AU of the Earth's orbit and has an absolute magnitude (H) of 22.0 or smaller, which corresponds to a diameter or 150 m or larger (assuming a visual albedo of 0.13). 1999 JU₃ is the primary target of the Hayabusa-2 probe scheduled to launch in 2014 by the Japan Aerospace Exploration Agency (JAXA). The Hayabusa-2 mission timeline would allow reconnaissance data to be acquired before the ARM spacecraft would need to launch. Assuming a Falcon Heavy ELV delivery to TLI, the ARM spacecraft would depart Earth in May of 2019, arrive at 1999 JU₃ in the beginning of 2021, and return to cislunar space at the end of 2025 with ~40 t. 1999 RQ₃₆ is a B-Type PHA (~500 m diameter) and is the primary target of NASA's OSIRIS-REx mission, which is scheduled to launch in 2016. For this target we would also have some initial reconnaissance data before launch. and the ARM spacecraft would depart Earth in November of 2018, arrive at 1999 RQ₃₆ in November of 2021, and return to cislunar in October of 2025 with ~32 t, again assuming a Falcon Heavy ELV delivery to TLI. Finally, 2008 EV₅

is a C-Type PHA (~450 m diameter) and the new primary target for the MarcoPolo-R mission currently under study within the Cosmic Vision program of the European Space Agency (ESA). 2008 EV₅ is also a possible future human mission target. MarcoPolo-R's proposed launch window is 2020-2024 [12], so return dates for this target would be later than 2025 in order for precursor information to be available. Approximately 37 t of material from 2008 EV₅ could be returned by the end of 2025, but this is likely too early to be compatible with MarcoPolo-R's currently proposed mission timeline.

4. Benefits of the Asteroid Retrieval Mission

There are many important benefits that would result from the successful completion of an Asteroid Retrieval Mission, and the subsequent successful processing of the returned materials. They include providing a near-Earth source of space resources for human and robotic space exploration, developing technologies and techniques to enable a future space-based economy based on the processing of asteroidal materials, and providing invaluable operational experience critical to future planetary defense efforts. This mission will offer an attractive near-term destination for human missions that can be leveraged to develop systems and operational experience for eventual human operations in the vicinity of a NEA in deep space or the Martian moons, Phobos and Deimos. It will also allow repeated crew visits to a NEA for extended periods of time before embarking on longer duration missions to more distant NEAs. The returned asteroidal material also provides extensive opportunities for commercial, scientific, academic, and international cooperation.

4.1 Space Resources

Although a case can be made that any mass in space can be useful, bringing back the right type of asteroidal materials will be critical to the future utilization of space resources. Materials like volatiles, metals, and carbon will be highly prized, and the difficulty of processing the raw materials could likely "make or break" efforts to include in-situ resource utilization (ISRU) as an integral part of human space exploration and settlement. The critical space resource is water, which can be used for propellants, radiation shielding, thermal control, human consumption, non-potable applications (plant growth, cleaning, etc.), along with many other uses. A 1,000-ton carbonaceous NEA could provide as much as 200 metric tons of water. Oxygen, which can be produced by electrolyzing the extracted water or by processing the various oxides found in asteroids, is also an extremely valuable commodity. Atomic oxygen comprises approximately 40% of the mass of a C-type asteroid. The paradigm shift enabled by the ARM concept would be to allow in-situ resources to initially be used at the human mission departure location (i.e., cislunar space), versus at the deep-space mission destination. This approach eliminates, or drastically reduces, the risk associated with leveraging ISRU for human deep-space missions to NEAs, the Martian moons, the surface of Mars, the main asteroid belt, and beyond. Also, the testing and validation of extraction and processing equipment and methods would enable the large-scale commercial extraction of space resources to become a reality. Just as NASA's rocket research helped launch the modern space age and the current Earth-to-orbit capabilities being implemented by commercial launch companies, the successful completion of the ARM would help companies develop an independent capability to retrieve asteroidal resources in heliocentric space and position them at advantageous locations for processing, along with providing valuable information regarding their nature.

4.2 Technologies and Operations

The demonstration of high-power, low-thrust SEP spacecraft to move payloads with masses of ~15-50 metric tons is extremely valuable for future space mission applications. The SEP spacecraft can be used to preposition large payloads to support human missions, and could be used as the main propulsion system in an excursion vehicle operating around low-gravity bodies such as asteroids, comets, and small moons like Phobos and Deimos (see Figure 8). The SEP could also provide the efficient propulsive capability to support a multi-target robotic precursor mission to explore several NEAs. When not being used for propulsive maneuvers, the high-power accompanying the SEP system could support a new class of robotic missions that utilize the abundant power to operate instruments that have historically been forced to minimize their power consumption. The capture mechanisms and proximity operations experience gained could have applications in other domains, such as orbital debris and derelict satellite cleanup, particularly when used in conjunction with the SEP system.

4.3 Science and Learning

In addition to the scientific knowledge gained by incorporating high-power SEP into robotic missions, the return of a primitive carbonaceous asteroid would help improve our scientific understanding of small bodies and their role in solar system processes and the formation of life on Earth and possibly on other planetary bodies. Although multiple tons of samples are most applicable for resource extraction, the ability to investigate a much larger sample and return multi-kilogram samples to terrestrial laboratories would provide additional contextual understanding of the recovered samples. Additionally, a robust observation and characterization campaign will



Figure 8: SEP-based excursion vehicle concept for a human NEA mission (image credit: NASA/AMA, Inc.).

also significantly increase what is known about NEAs (densities, spin rates, etc.), and examination of an entire NEA will provide valuable information regarding their internal structure. Another important benefit that is often difficult to quantify, would be to help motivate students around the world to pursue careers in science, technology, engineering, and math (STEM) and create the first generation of high-tech space miners in human history.

4.4 Long-term Benefits

Farther in the future, the materials extracted would help construct space colonies and support growing food in water-rich soils derived from carbonaceous regolith. The returned asteroidal material could even provide an orbiting platform/counter-weight for a lunar space elevator [13] and transfer depot. This could significantly accelerate the permanent settlement of the Moon, and could in turn allow electromagnetic launch of asteroidal and lunar resources from the lunar surface in support of other deep-space missions (e.g., missions to the Mars system, transport cyclers, and beyond), and could ultimately enable the cost-effective return of high-value extraterrestrial materials to markets on Earth. The combination of asteroidal resources, space elevators, and a permanent colony and staging location on the Moon would open up the solar system, and eventually the stars, to future human settlement.

5. Synergy with Planetary Defense

In addition to the direct and indirect benefits for mankind mentioned above, the ARM could have a profound influence on planetary defense efforts. The technologies and operational approaches that are required to efficiently travel to, interact with, and maneuver an asteroid are directly applicable to averting an impact from one of these small bodies. Also, it is likely that they are extensible to averting an impact with a cometary nucleus or fragment. The key is the symbiotic relationship between planetary defense and the other primary areas of interest – space resources, science, and human exploration and settlement. The ARM will validate many technologies and operational techniques that will accelerate commercial efforts to mine asteroidal materials, which in turn will motivate a new era in asteroid discovery and characterization, and ultimately provide a foundation for a planetary defense system capable of protecting the Earth from a wide range of future impactors. Additionally, the successful retrieval of a small NEA, or a massive amount from a large one, would help direct resources and attention to the study of near-Earth objects and thus foster additional efforts that focus on the challenge of defending our planet from future impacts. Finally, the processed materials themselves (e.g., water-derived, high-specific impulse chemical propellants) and the SEP spacecraft capable of transferring large masses through heliocentric space could also be used for planetary defense.

5.1 The Impact Dilemma

No dedicated planetary defense system is currently known to be under development by any country, and it is unlikely that one will be funded in the foreseeable future due to the infrequency of Earth impacts. There exist two fundamental and closely related questions that need to be answered when considering the issue of planetary defense. First, would mankind actually take defensive action in sufficient time to avert an impact? Currently, due to the fact that the vast majority of NEOs capable of local or regional damage haven't been discovered, the highest probability outcome is that we will have little to no warning time, and we would not be able to take action in time. Continued efforts to discover and characterize more of the NEO population will one day shift this probability, but there will likely always remain some threat, including uncataloged NEAs and long-period comets, that cannot be identified with sufficient warning time. More warning time is better, but even if we were to find an object believed to be on an impact trajectory several decades in the future, the uncertainties in the accuracy of the orbit and the significant amount of time could result in a "wait and see" attitude that could hinder efforts to avert the impact until its possible impact with the Earth becomes a certainty. At that point, it again may be too late to successfully avert the impact. If mankind takes the position that it shouldn't wait to develop and implement a planetary defense capability until we have identified an Earth impacting asteroid or comet because the risk is too great, then the second question arises. How do we justify and secure the timely funding to develop a planetary defense system which might not be used for many decades, centuries, millennia, or longer? A dedicated planetary defense system is "a tough sell" to both governments and the general public when placed in competition with the myriad of other pressing needs. Public reaction to more frequent small impactors, such as the Chelyabinsk Event in February of 2013, may garner a burst of media and political attention, but it is not likely to be sustainable as other terrestrial issues regain the "spotlight." So the "impact dilemma" forces us to ask "how do we develop and implement a planetary defense capability in time to stop an impact if we can't develop and implement the capability in time?"

The answer to this dilemma requires us to think long-term and synergistically. Systems that provide productivity and value, are justifiable from a cost standpoint, are constantly available and operationally ready, and can be effectively repurposed during an emergency, can resolve this dilemma. A good analogy is trying to convince a city government in Florida to purchase snowplows. It has snowed in Florida in the past, and it could again, but a major blizzard is an extremely low-probability event and maintaining a dedicated fleet of snowplows for such an emergency is not cost-effective. An alternative approach, that can actually be economically attractive, is to repurpose some existing capability when an emergency occurs, such as substituting snowplows with bulldozers. Normally, the bulldozers are being operated for various activities that have economic value, and personnel are trained and proficient in operating them. If the "unthinkable" happens, and a major snow storm strikes the area, the bulldozers, and their trained operators, can be called upon to help mitigate the effects of the storm and avert the consequences of this significant local or regional event. The bulldozers may not be as effective as a dedicated fleet of snowplows, but are a more logical and politically acceptable approach.

In a similar manner, this approach can be implemented to overcome the impact dilemma. The approach is to initiate a campaign to find and characterize these asteroidal and cometary bodies, that represent both resources and potential threats, and at the same time develop the technologies, capabilities, systems, and operational approaches for their utilization in space so that we will be prepared to avert, or at least mitigate, the threat from the next NEO on a Earth-impacting trajectory. By establishing the capability to move and to process these objects and leverage their vast economic potential, we will take the first credible step to providing a planetary defense system for our planet.

5.2 Technologies and Operations

Many of the ARM technologies and operational approaches will be applicable to planetary defense efforts. These include the operations and systems associated with the NEA rendezvous, station-keeping, and approach mission phases utilizing a low-thrust, high-power SEP spacecraft, along with interacting with, capturing, maneuvering, and processing the massive amounts of material associated with this mission. Foremost, the use of a SEP spacecraft to deliberately alter the orbit of an asteroid is a direct demonstration of a rudimentary planetary defense capability at a small, safe, and affordable scale. Since an impactor ~7 meters in diameter does not represent a credible threat to Earth, unless possibly if it is a solid iron-nickel object, capturing an entire small asteroid will have limited benefits when dealing with a large, Earth-threatening NEO (diameter of ~30 m or larger). Conversely, the systems and techniques that can successfully operate near and on a larger NEA will be directly applicable to future planetary defense efforts.

Technologies and techniques that allow the anchoring to a small planetary body could be critical to planetary defense, as well as mining operations. Many options for the deflection or disruption of NEOs will be possible if

the capability to effectively anchor to the surface is achievable. The lack of effective reaction forces normal to an asteroid or comet's surface makes anchoring problematic. One approach is to tunnel while exerting pressure against the walls to provide stabilization. In this case, the reaction forces are provided by the surface regolith itself. This may be complicated by the potentially porous or fractured low-strength asteroidal material, but should be possible. Being able to effectively tunnel deep below the surface would assist in understanding the structure of an impactor, as well as allow the emplacement of explosive devices (conventional or nuclear) at a location where they can be the most effective. The amount of warning time required to neutralize a confirmed impactor could be significantly decreased if robust anchoring and tunneling techniques are available.

The planetary defense technique of utilizing a kinetic impact is a viable approach for deflecting an impactor, but there is a great deal of uncertainty regarding its effectiveness. This is primarily due to a lack of knowledge about how a kinetic impact device would interact with the regolith and what momentum multiplication effect would be achieved. The capability to characterize the structure of the asteroid, and in particular the surface layers, would help to significantly reduce the uncertainty of the momentum transferred to the NEO.

The development and operational use of various capture mechanisms would be extremely valuable for planetary defense efforts. A wide variety of systems that interact with the surface could be used for acquiring asteroidal material, and different types of mechanisms may be needed to handle the wide range of NEO regolith mechanics and geotechnical properties that can be expected. Regardless of the techniques employed, having the ability to secure tens or hundreds of metric tons of asteroidal material would help in providing additional mass to increase the effectiveness of the gravity tractor concept or a kinetic impact deflection.

Rendezvous and proximity operations with a NEO, as well as navigation to the NEO and maneuvering a large mass with a SEP spacecraft would be directly applicable to planetary defense planning and implementation. A slow push approach with a SEP system could be used to deflect an impactor of a given mass and with sufficient warning time.

The dust environment is dependent on the particular target and could vary significantly over time and location. We will not necessarily know the dust environment of a future impactor, but understanding the mechanisms that trigger dust expulsion, along with its levitation and settling behavior, are important areas of understanding that could aid successful planetary defense efforts. Also, understanding how to operate in a manner that minimizes surface perturbations, if necessary, will yield valuable operational experience. Dust mitigation will be particularly important for the gravity tractor concept, which will be required to conduct station-keeping operations at close proximity utilizing the efficient SEP thrusters. Quantifying the dust hazard, gaining a better understanding of the stand-off distance requirements, and designing efficient systems and control approaches will be important for future defensive operations.

The technology and operations discussed here are the principle areas where the ARM could contribute to planetary defense efforts. There are likely other areas, as well as unknown issues that will arise, and hopefully be solved, during a mission to interact with an asteroid and move it or part of it. Finally, in addition to the specific benefits of the technologies and operation readiness provided by the ARM mission, as well as follow-on missions to other targets, one very important benefit will be to gain a better general understanding of NEOs, and the range of conditions and difficulties that they present. Ultimately, we will not be able to choose the object that threatens the Earth next, and we will have to be prepared to be able to deflect or disrupt a wide variety of impactors.

5.3 Options for Asteroid Retrieval Infrastructure to Provide Planetary Defense

As mentioned earlier, a robotic ARM spacecraft that is capable of returning up to 1000 metric tons of asteroidal material could deliver significant amounts of mass for a kinetic impact deflection or improve the effectiveness of a gravity tractor concept. It could also deliver various payloads to the target. In combination with the ~40 kW available from the power system, a pulsed laser ablation device could be used for slow, controlled orbit modification as described in [14]. Due to the power level and conversion losses, the warning time would need to be significant for this type of deflection effort. With less warning time, the payload delivered by the SEP spacecraft could be a nuclear device for a stand-off explosion, or with sufficient supporting systems to tunnel or penetrate into the target, a subsurface detonation could be implemented. For a kinetic impact or nuclear detonation, a separable spacecraft would be beneficial to deliver the payload and allow instruments on the SEP spacecraft to monitor the deflection or disruption. Finally, a ubiquitous asteroid retrieval and resource extraction infrastructure could provide the foundation of an "on call" planetary defense system, where a SEP fleet capable of propelling large masses could deliver payloads to deflect or disrupt a confirmed impactor in an efficient and timely manner.

6. Future Work

There are many areas of future work for the ARM concept that are relevant to planetary defense efforts, resource retrieval efforts, and scientific and human exploration efforts. Investigating more complex trajectories incorporating multi-planet gravity assists, specifically Venus (outbound) and Earth, could increase the returnable mass. Additionally, the use of in-situ resources for augmenting the propulsive capability of the SEP and extracting compatible electric propellants, such as magnesium, could significantly increase the amount of mass that can be returned to cislunar space. Magnesium could comprise ~10-15% of C-type asteroid's mass [15]. Also, further work is needed to quantify how the SEP spacecraft could effectively pre-deploy assets needed for a crewed NEA mission, and the possible benefits of having crew participate in the capture and collection process of asteroidal material. Finally, investigations should continue to explore innovative methods to leverage SEP spacecraft, including more powerful systems and the use of modular SEP spacecraft "ganged" together, along with space-based infrastructure, to provide a robust ability to divert threatening asteroids and comets.

7. Conclusions

This paper has provided an overview of the Asteroid Retrieval Mission concept along with a discussion of important mission considerations, possible operational approaches and options, key technologies and capabilities, and potential mission benefits. It is the symbiotic interdependency between the industrialization of space resources, human exploration and settlement of the solar system, our scientific understanding of our solar system including its creation and evolution, and our imperative to protect our planet from future impacts that can provide the motivation to drive the discovery and characterization of more NEAs, along with the development of technologies, systems, and operational approaches and techniques that can benefit all of these important areas. A prolific and robust asteroid retrieval and processing infrastructure could potentially assure that one or more ARM spacecraft could provide the delivery of payloads for a deflection or disruption effort, or provide the necessary mass and navigation to provide a kinetic impact against a threatening asteroid or comet. These same systems and capabilities that can expand human presence throughout the solar system and open up the vast economic potential of space can be called upon, when needed, to provide an effective planetary defense system against Earth-impacting comets and asteroids.

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