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

Presented by Dan Mazanek[1]

Co-authors: John Brophy[2] and Gabe Merrill[1]

[1]NASA Langley Research Center; [2]Jet Propulsion Laboratory

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Background

- **The idea of utilizing asteroidal resources is not new**
  - 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*
  - 1977 – NASA's Dr. Brian O'Leary proposed using mass drivers to move Earth-approaching Apollo and Amor asteroids to Earth's vicinity
  - 1997 – Dr. John S. Lewis detailed how we can extract the vast resources available from our solar system in the influential book *Mining the Sky: Untold Riches from the Asteroids, Comets, and Planets*
- **September 2011 and February 2012 – Asteroid Retrieval Mission (ARM) Study at Caltech's Keck Institute for Space Studies (KISS)**
  - Examined the feasibility of returning a small (~7 m diameter) near-Earth asteroid (NEA), or part of a large NEA, to cislunar space
  - Utilize robotic 50 kW-class solar electric propulsion (SEP) vehicle and currently available technologies (40 kW available to the electric propulsion system)
  - John Brophy (Co-Leader along with Louis Friedman and Fred Culick) and Dan Mazanek were KISS ARM study members

Recent Events

- **Recent events have elevated the public's awareness of the potential of space resources and have highlighted the vulnerability of Earth and its inhabitants**

- **Planetary Resources, Inc. (April 2012) and Deep Space Industries (January 2013) announce plans to mine asteroids**

- **Two asteroid encounters with Earth on February 15, 2013**
  - Record close approach of the roughly 30-meter NEA 2012 DA_{14} within ~27,700 km of the Earth's surface
  - Unrelated meteor break up in the atmosphere just southwest of the Chelyabinsk, Russia damaging buildings and injuring over 1500 people

- **Comet C/2013 A1 (Siding Springs) discovered in January of 2013**
  - Long-period comet (LPC) with a nucleus likely several kilometers in diameter
  - Extraordinarily close approach to Mars on the evening of October 19, 2014 has a small, but non-zero probability of impact

The "Impact Dilemma"

- **Mankind has no dedicated planetary defense system (only observation program), and it's unlikely one will be funded in the future due to the infrequency of impacts**
- **Would mankind take action in sufficient time to avert an impact?**
  - Vast majority of Near-Earth Objects (NEOs) capable of local or regional damage are undiscovered – highest probability outcome is that we will have little to no warning time
  - There will always be some threat that cannot be identified with sufficient warning time – uncataloged NEOs and LPCs
  - Even with significant warning time, orbit uncertainties could result in a "wait and see" attitude that could hinder efforts until impact becomes a certainty – too late?!
- **If we don't want to wait, how do we develop a planetary defense system which might not be used for many decades, centuries, millennia, or longer?**
  - A dedicated system is "a tough sell" to both governments and the general public
  - Public reaction to more frequent small impacts, such as the Chelyabinsk Event, is not likely to be sustainable

> "Impact dilemma": 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?

Long-term and Synergistic Approach

- **This impact dilemma requires us to think long-term and synergistically**
- **Systems approaches that can resolve this dilemma:**
  - Provide productivity and value
  - Are justifiable from a cost standpoint
  - Are constantly available and operationally ready
  - Can be effectively repurposed during an emergency
- **Snowplows for bulldozers analogy**
  - It has snowed in Florida in the past, and it could again, but a major blizzard is an extremely low-probability event
  - Maintaining a dedicated fleet of snowplows is not cost-effective and politically intractable
  - Bulldozers can be operated for various activities that have economic value and the personnel are trained and proficient in operating them
  - The bulldozers and their operators can be called upon to help mitigate the effects of the blizzard

ARM-based Solution to the Impact Dilemma

- **In a similar manner, this approach can be implemented to overcome the impact dilemma**
  - Initiate a campaign to find and characterize near-Earth asteroids and comets, that represent <u>both</u> resources and potential threats
  - Develop the technologies, capabilities, systems, and operational approaches for their utilization in space so that we will be prepared to divert, or at least mitigate, the threat from the next Earth impactor
  - Approach should be capable of responding to a range of warning times
- **The Asteroid Retrieval Mission could provide the first step to an integrated solution**
  - Establish the capability to efficiently move and to process NEOs and leverage their vast economic potential
  - Sustainable and profitable in the long term
  - Foundation of an “on call” planetary defense system – no development and launch

Motivation for the ARM

- What is the primary motivation for the Asteroid Retrieval Mission?
- Is it for planetary defense? No, but it helps us in our understanding of future impactors and offers the potential to be leveraged in an emergency.
- Is it for science? No, but extensive science will be performed and a tremendous amount of knowledge will be gained.
- Is it to practice for future deep-space human missions to NEAs and the Martian moons? No, but learning how to operate near small planetary bodies and interact with them is critical for mission success.

The primary motivation should be to help enable the utilization of space-based resources for exploration and the creation of a viable, sustainable space-based economy for the benefit of all mankind.

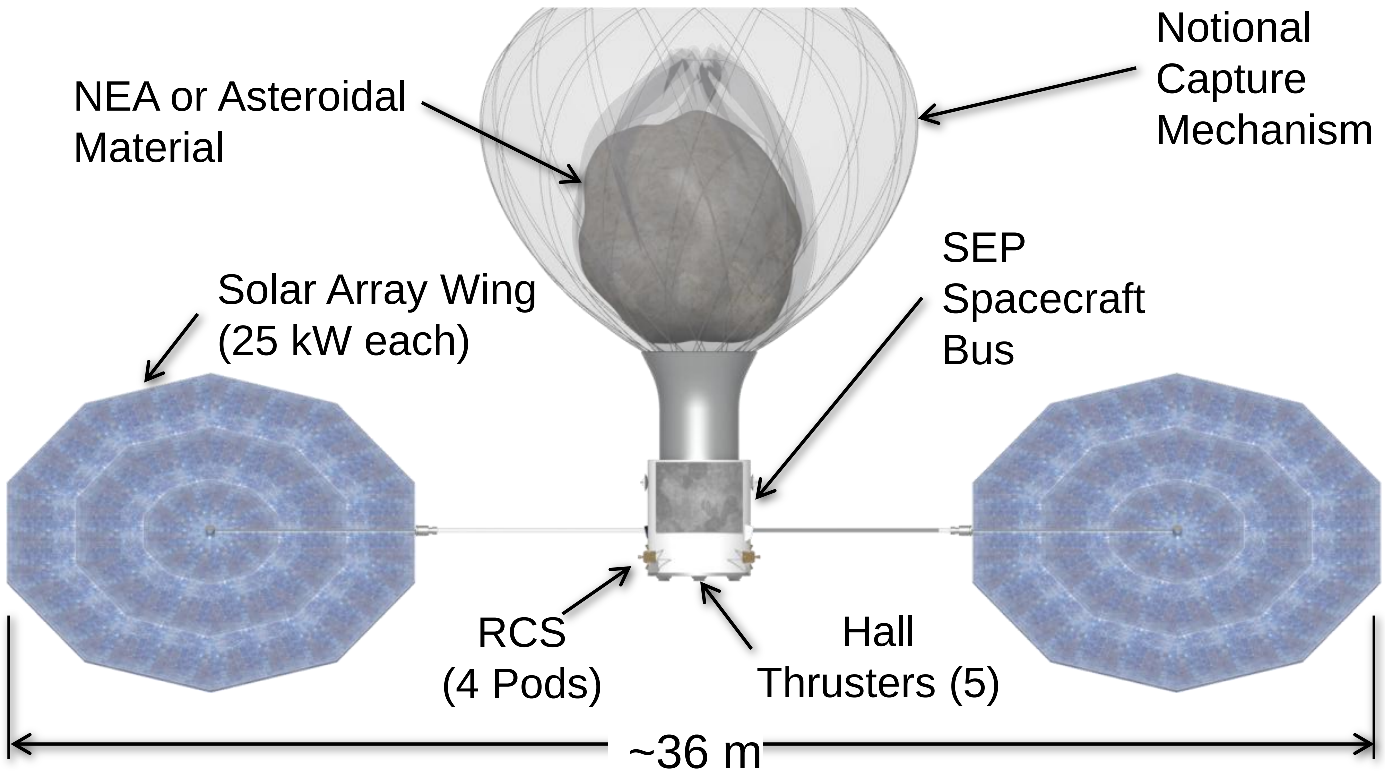
New paradigm: bring the resources for human missions initially to the point of departure vs. the destination!

The Asteroid Retrieval Mission Concept

- **50 kW-class SEP spacecraft (~40 kW available to the electric propulsion system end-of-life) accompanied by a suitable capture system to acquire and return a small NEA, or part of a large NEA, to cislunar space**

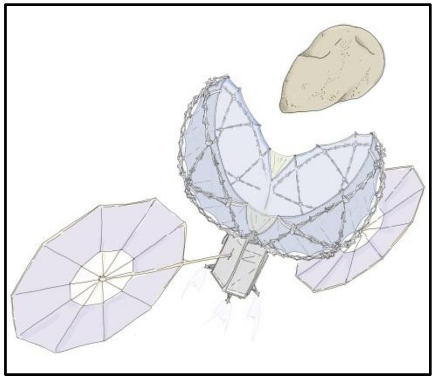
- **Returned mass from this initial mission is anticipated to be up to 1,000 metric tons**
  - Depends on the orbit of the target NEA and the thrust-to-weight and control authority of the SEP vehicle
  - Even larger masses could be returned in the future as technological capability and operational experience improve
  - Eventually, cometary material could be captured and returned

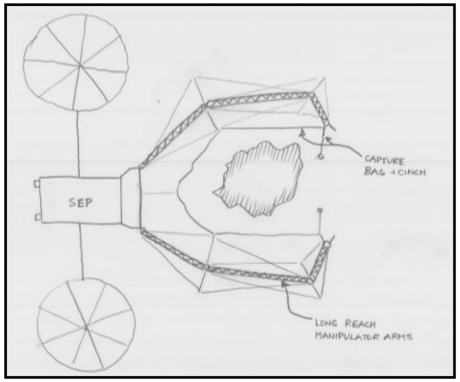
Asteroid Retrieval Mission (ARM) Configuration

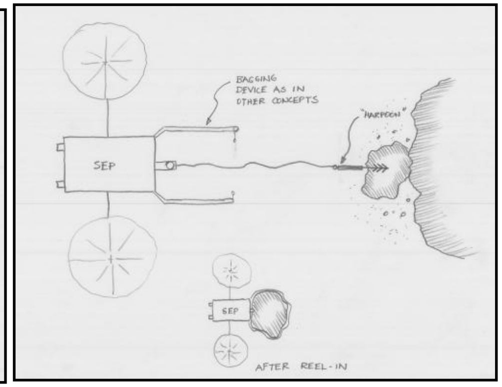


- **40 kW-class (end-of-life) SEP spacecraft with five 10-kW Hall thrusters using xenon (Xe) as the propellant with a specific impulse (I_{sp}) of 3000 s**
  - ~4-5 t dry mass and ~12-18 t wet mass (dependent on launch vehicle and delivery orbit)
  - Hydrazine (biprop or mono-prop) Reaction Control System (RCS) for capture and control operations
- **A variety of capture mechanism approaches could be implemented**

Capture System and Configuration Options







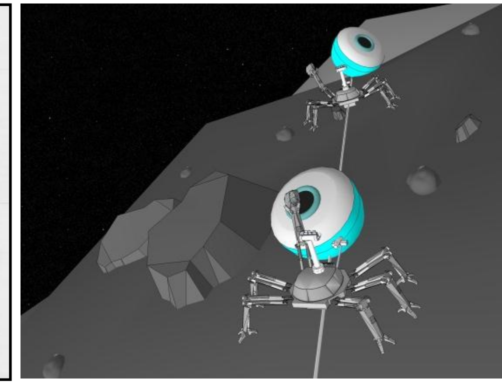
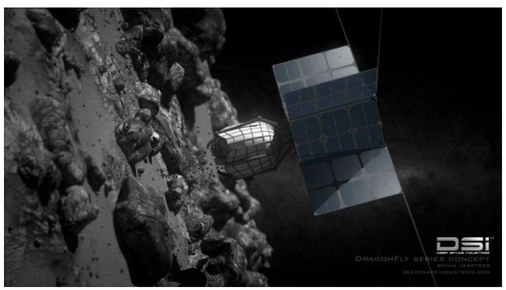


Image credits: NASA/AMA, Inc.



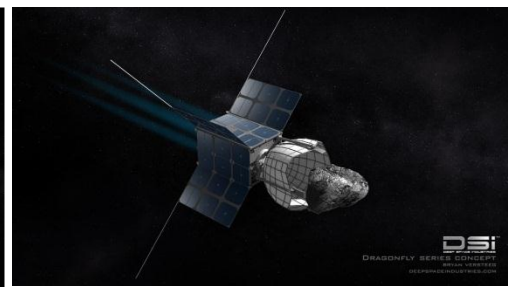


Image Credits: Bryan Versteeg / Deep Space Industries

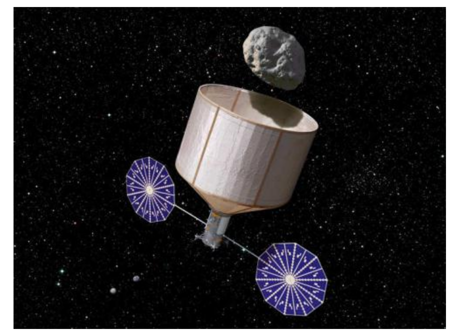
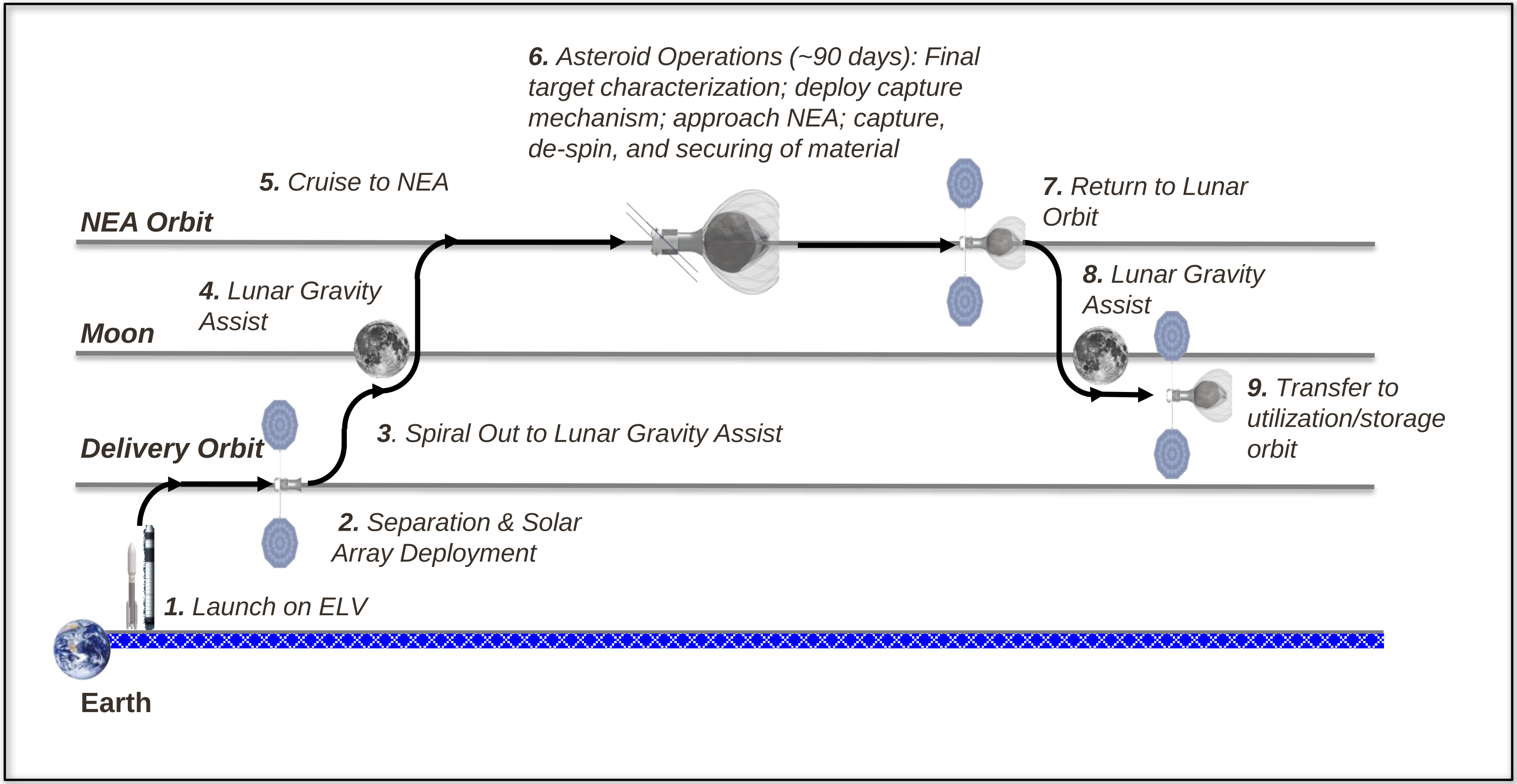


Image Credit: Rick Sternbach / KISS

- **Many different capture mechanisms can be combined with a SEP spacecraft**
- **Single spacecraft vs. separable spacecraft**
  - A separable spacecraft is likely more expensive, would necessitate the need for autonomous rendezvous and docking with the SEP vehicle, and would have less energy capability once separated
  - However, the ability to monitor the NEA capture and control operations, particularly for returning part of a large one, might outweigh the disadvantages of a separable system

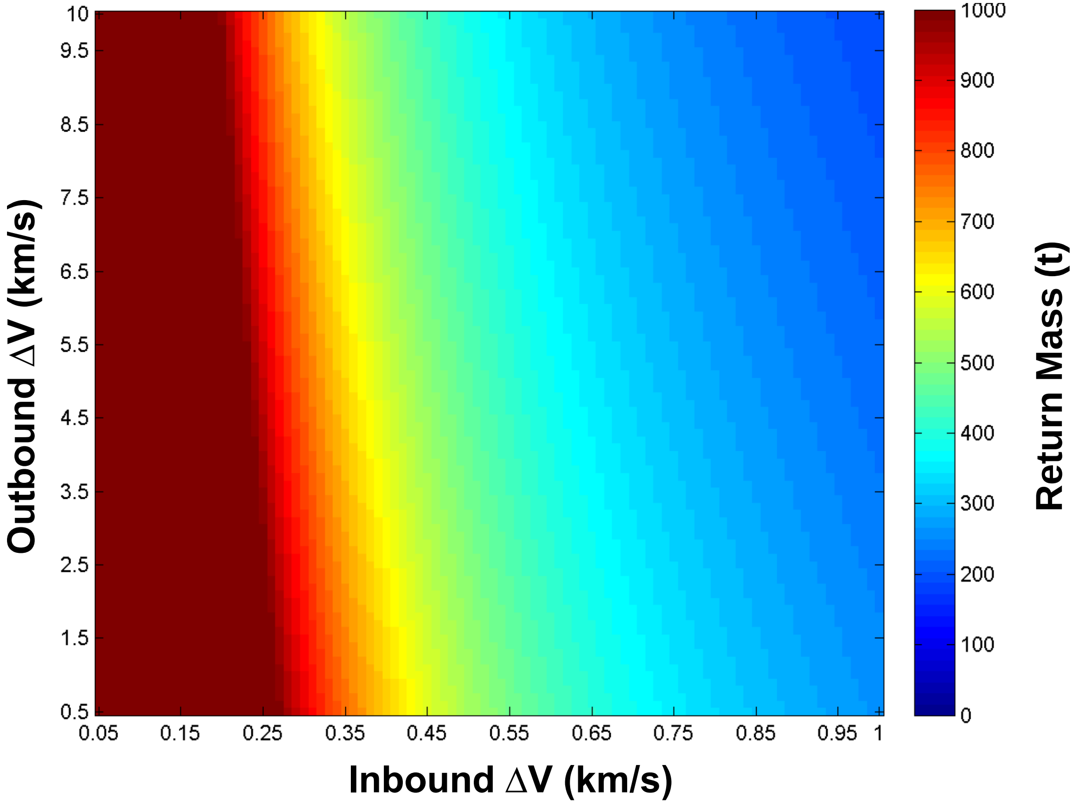
Typical ARM Mission Sequence



The robotic return mission is one component of a multi-step campaign to find, characterize, return, explore, and utilize near-Earth asteroids.

Return Mass

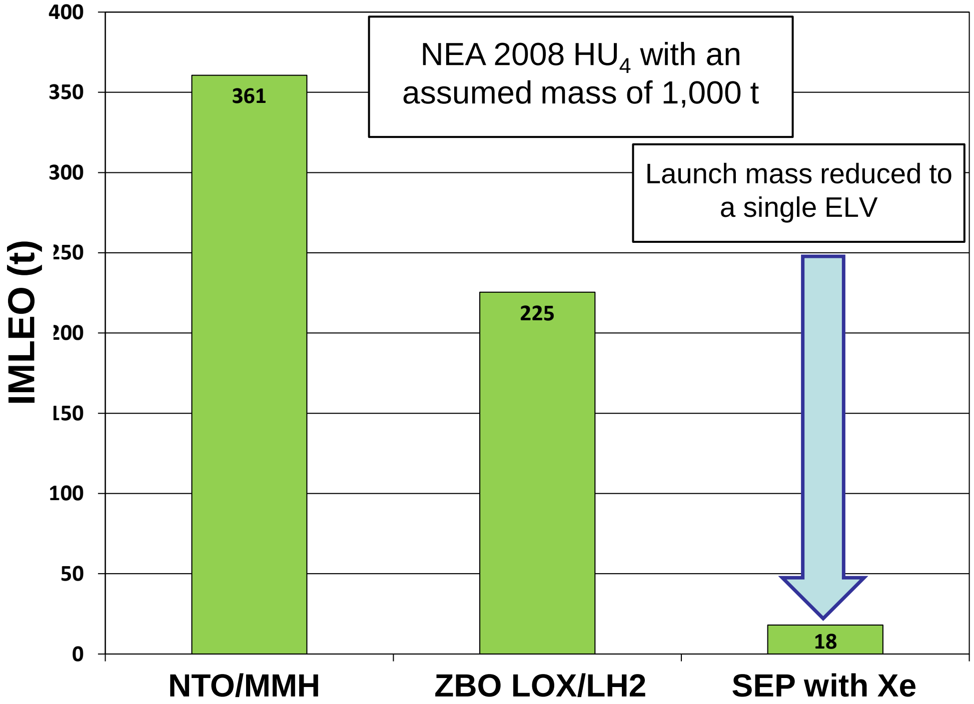
- **The return mass is dominated by the inbound heliocentric and cislunar capture ΔV requirements**



Return mass in metric tons as a function of the outbound and inbound ΔV (including capture into a stable orbit)
40 kW electric propulsion, Isp = 3000 s, LEO delivery on an Atlas V 551 ELV

Solar Electric Propulsion – Enabling Technology

- **Low-thrust solar electric propulsion is the enabling technology for the ARM**
- **High specific impulse (Isp) of up to 3000 s for 10 kW Hall thrusters**
- **SEP using xenon (Xe) propellant requires much less Initial Mass in Low-Earth Orbit (IMLEO) than chemical propulsion**



- ~20 times less than low-efficiency, space-storable propellant, such as nitrogen tetroxide (NTO) and mono-methyl hydrazine (MMH)
- ~12 times less than high-efficiency, liquid oxygen/liquid hydrogen (LOX/ LH2) propulsion assumed to have zero-boil-off (ZBO) cryogenic storage capability

Retrieval Options

Retrieve an Entire Small NEA

- **Pros:** Many targets (potentially millions); single, free-floating target may simplify capture operations; more likely to be coherent or monolithic
- **Cons:** Lack of sufficiently characterized targets; large size/density uncertainty; potential high spin rate likely increases capture complexity; difficult to determine spectral type

Retrieve Part of a Large NEA

- **Pros:** Optimize return mass; better able to select a well-characterized target with desirable resources; likely low spin rate simplifies capture and control; easier to determine spectral type; 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)
- **Cons:** Capture material in presence of main body and confirm that material is detached/detachable; likely fewer targets with low ΔV for return

Retrieve a NEA Moonlet (Secondary Body)

- **Pros:** 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 is complete
- **Cons:** 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: Need a more comprehensive remote NEO survey and characterization capability (i.e., space-based infrared telescope) and extremely low-cost robotic precursors with basic characterization capability (nanosatellites or smaller)

Target Type

- **The type of asteroid selected is a critical decision – “Follow the water!”**
- **Primary *initial* candidate is a water-rich carbonaceous (C-type) NEA**
  - 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
  - C-type NEAs could provide vast quantities of water-rich material for resource extraction. Hydrated minerals can consist of up to 40% extractable volatiles by mass (~20% water and ~20% carbon-bearing compounds).
  - Low compressive strength, which simplifies cutting, crushing, and processing – **<u>could be breakable by hand!</u>**
  - Significant concentrations of many metals, particularly iron and nickel, hydrocarbons, magnesium, and various minerals
  - Also contain amino acids, such as glycine, alanine and glutamic acid – the building blocks of life
  - Believed to comprise a significant percentage of the NEA population (dark – biased observations)

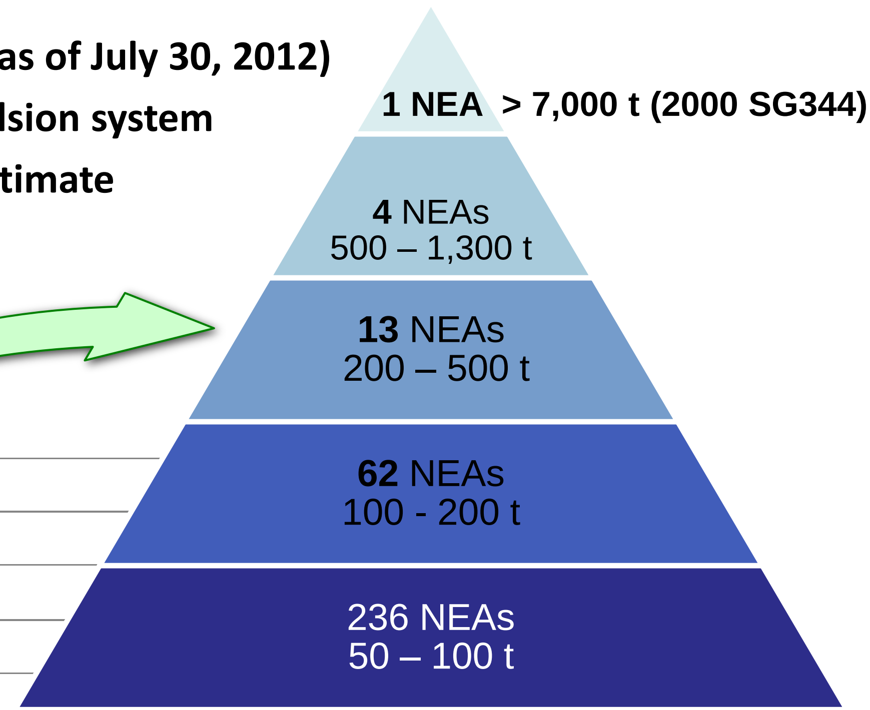
723 gram fragment of the Murchison CM2 carbonaceous chondrite meteorite
(photo credit: Jim Strope)

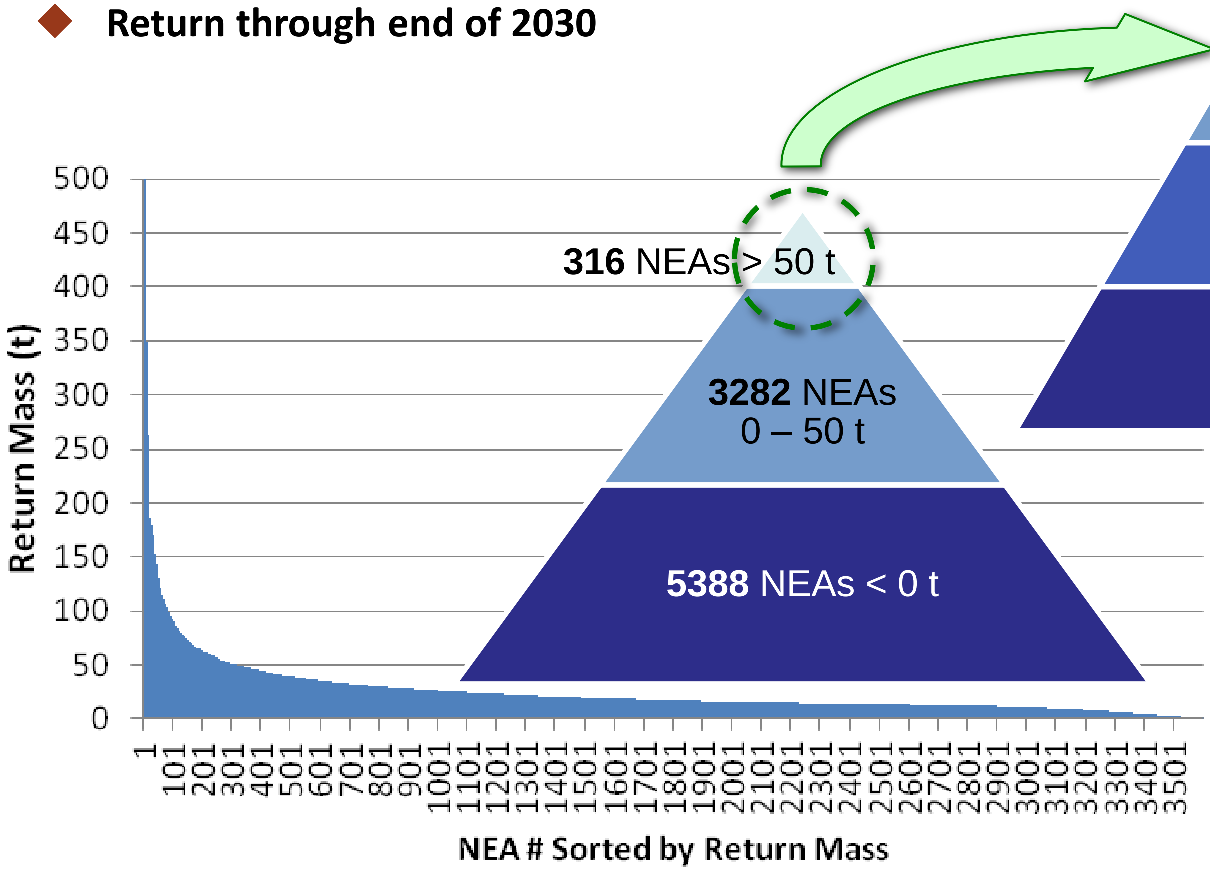
Target Size and Uncertainties

- **Based on visual albedo, the estimated diameter of a NEA can vary by 450%**
  - NEA with an absolute magnitude **(H) of 28.0** could be as small as **4.4 m** in diameter (visible albedo of 0.60), or as large as **19.5 m** (visible albedo of 0.03)
  - **Volume** could vary by a factor of **~90**, and density uncertainty could add an additional uncertainty factor of 3+ to the mass
  - Density of 3 g/cm^3 ⇨ **4.4 m** NEA mass = ~**130 t** vs. **19.5** m NEA mass = **11,700 t**!
- **Small NEAs tend to be fast spinners – 2010 JL88 (diameter 8-34 m) rotates once every 24.5 seconds!**
- **It is difficult to remotely determine the spectral type of a <u>very</u> small NEA**
- **Returning part of large NEA affords mission flexibility but likely requires a robotic precursor**
  - Our limited robotic visits to large NEAs indicate that the presence of material ranging from dust to boulders, which could allow better selection of return mass
  - Targeting a NEA that has already been visited by a robotic precursor can verify that acceptable material is available for recovery
  - Most large NEAs are slow rotators, typically once every few hours or longer, and remote characterization is significantly easier (spectrometry and radar)

Return Mass Capability

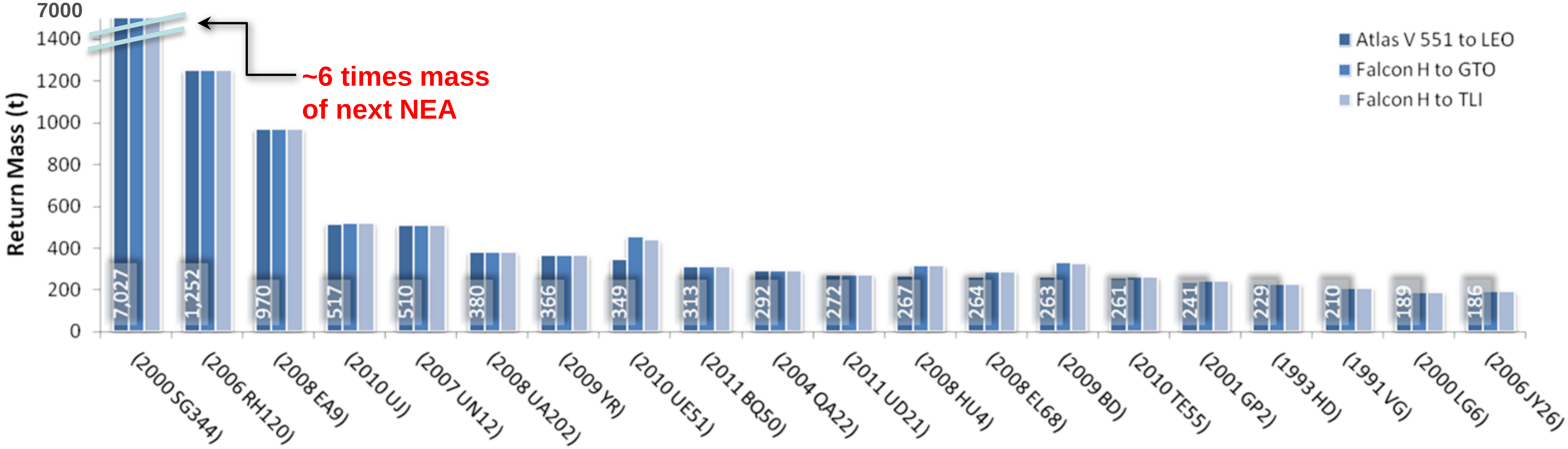
- 8986 NEAs in scan (Horizons Small-Body Database as of July 30, 2012)
- Atlas V 551 ELV to LEO and 40 kW to electric propulsion system
- Initial high-thrust Lambert scan provides a good estimate
- Departure after beginning of 2019
- Return through end of 2030





Return Mass – Available in Cis-Lunar Space by 2030

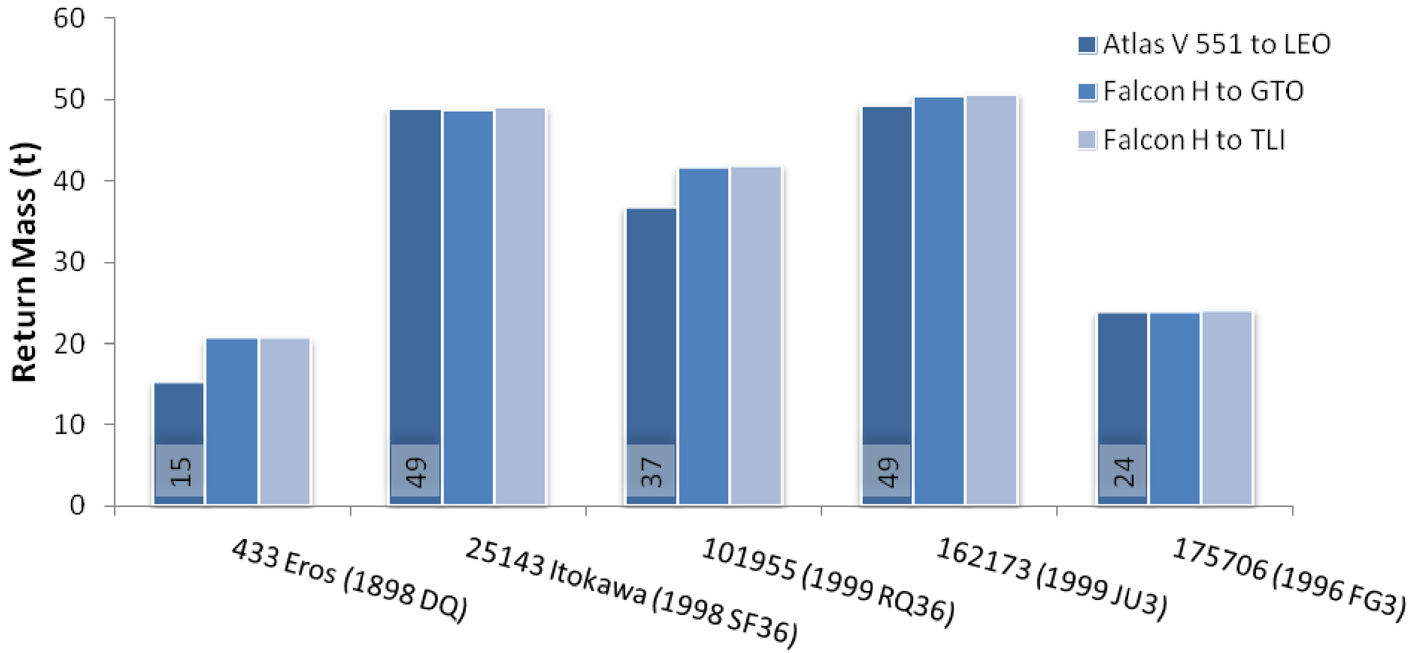
Top 20 NEA Return Masses of all NEA Targets (as of July 30, 2012)



- **Characteristics of the above NEAs are not known well**
- **2009 BD might be the right size, but its rotational characteristics and composition are uncertain**
- **<u>If</u> 2000 SG344 is a low-albedo, C-type NEA**
  - Could be up to 86 m in diameter and have a mass of ~800,000 t
  - Could contain **~160,000 t of water** – enough to sustain future space exploration and settlement efforts for the foreseeable future

Return Mass – Available in Cis-Lunar Space by 2030

NEA Targets Previously Visited or with Planned Robotic Missions



- Characteristics of the above NEAs are or will be well known
- 433 Eros and 25143 Itokawa are stony (S-Type) NEAs and others are carbonaceous (C/B-Type) – 1996 FG_3 is currently secondary target for MarcoPolo-R
- Returned mass is significantly lower than top targets, but may be sufficient for initial mission and provide sufficient materials for ISRU demonstrations

Benefits (1 of 2)

- **Near-Earth source of space resources for human and robotic space exploration and the permanent settlement of space**
- **Develop technologies and techniques to enable a future space-based economy based on the processing of asteroidal and cometary materials**
- **Develop systems and operational experience for eventual deep-space human operations in the vicinity of a NEA or the Martian moons**
- **SEP is enabling for a variety of space missions and architectures where high-efficiency, low-thrust transfers are applicable**
- **Provide systems and operational experience invaluable to future planetary defense**

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

Benefits (2 of 2)

- **Science and Learning**
  - Improve our scientific understanding of small bodies and their role in solar system processes and the formation of life on Earth and possibly elsewhere
  - Multi-kilogram samples to terrestrial laboratories would provide additional contextual understanding
  - Motivate students around the world to pursue careers in science, technology, engineering, and math and create the first generation of high-tech space miners in human history!

- **Long-term benefits**
  - Construction of space colonies and support the growth of food in water-rich soiled derived from carbonaceous regolith
  - Possible platform/counter-weight for a lunar space-elevator and transfer depot, which could allow electromagnetic launch of asteroidal and lunar resources from the lunar surface in support of other deep-space missions. Could ultimately permit the cost-effective return of materials to markets on Earth.

- **Many others...**

Synergies with Planetary Defense

- **Use of a 40 kW SEP 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**
  - Better understanding of NEOs and their environment (internal structure, geotechnical properties, momentum multiplication effect, dust, etc.)
  - Operations and systems associated with approach, rendezvous, and station-keeping mission phases, along with interacting with, capturing, maneuvering, and processing material
  - NEO anchoring and tunneling are critical to mining operations and human exploration, and could be critical for planetary defense
  - Maneuvering a large mass is directly applicable to planetary defense. A slow push approach with a SEP system, improving the effectiveness of the gravity tractor concept, or delivery of a laser ablator could be used to deflect an impactor of a given mass and with sufficient warning time.
- **Solving the "Impact Dilemma" by delivering significant amounts of mass for a kinetic impact deflection or delivering fast acting payloads, such as nuclear devices, to the target in a timely manner**

Future Work

- Investigate more complex trajectories incorporating multi-planet gravity assists to the increase return mass (i.e., Earth and Venus on outbound)

- Examine the use of in-situ resources for augmenting the SEP propulsive capability by extracting compatible electric propellants, such as magnesium, to increase return mass and operational capability

- Assess how the SEP system could effectively pre-deploy assets needed for a deep-space human NEA mission and the possible benefits of having crew participate in the capture and collection process of asteroidal material

- Explore innovative methods to leverage space-based infrastructure and SEP spacecraft, including more powerful systems and the use of modular spacecraft ganged together, to provide a robust ability to divert threatening asteroids and comets

Closing Remarks

- **This presentation 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**

- **The ARM concept could create a new paradigm for human space exploration**
  - Brings the in-situ resources to the point of departure vs. the destination
  - Allows us to integrate ISRU into exploration just as we rely on preplaced resources for transportation and development efforts on Earth

- **The 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 help provide an effective planetary defense system against Earth-impacting comets and asteroids**

Some Closing Thoughts Courtesy of Mark Twain

"The man with a new idea is a crank until the idea succeeds."

– *Following the Equator*

"There is no such thing as a new idea. It is impossible. We simply take a lot of old ideas and put them into a sort of mental kaleidoscope. We give them a turn and they make new and curious combinations. We keep on turning and making new combinations indefinitely; but they are the same old pieces of colored glass that have been in use through all the ages."

– *Mark Twain, a Biography*

Thank you for your time and attention.