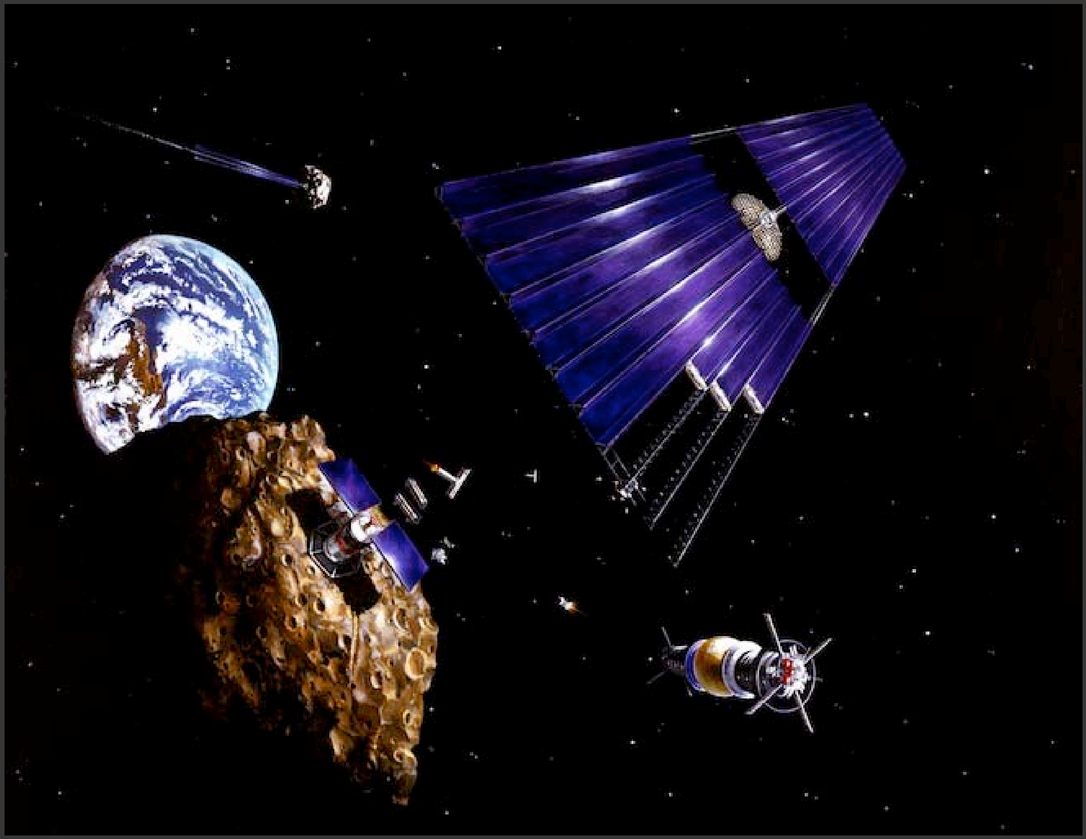
Asteroid Retrieval Feasibility



ESA ESTEC: March 14, 2012

Louis Friedman & Marco Tantardini

Keck INSTITUTE FOR SPACE STUDIES

THE PLANETARY SOCIETY

CALTECH KECK INSTITUTE FOR SPACE STUDIES (KISS)

STUDY Co-Leads

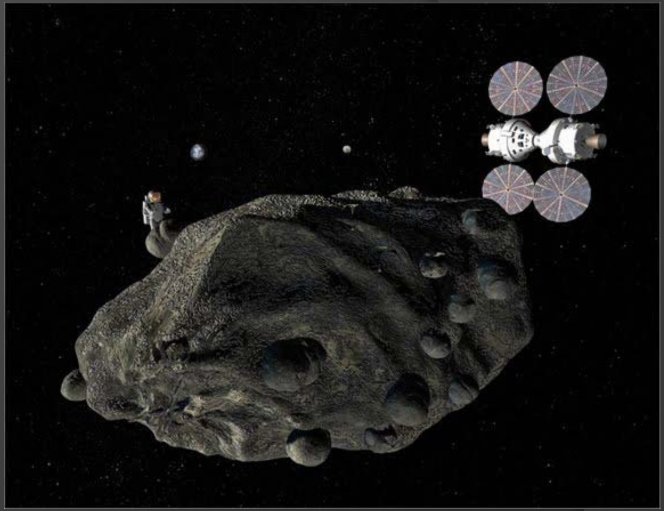
John Brophy (NASA JPL)
Fred Culick (Caltech)
Louis Friedman (The Planetary Society)

- Carl Allen (NASA JSC)
- David Baughman (Naval Postgraduate School)
- Julie Bellerose (NASA ARC)
- Bruce Betts (The Planetary Society)
- Mike Brown (Caltech)
- Michael Busch (UCLA)
- John Casani (NASA JPL)
- Marcello Coradini (ESA)
- John Dankanich (NASA GRC)
- Paul Dimotakis (Caltech)
- Martin Elvis (Harvard-Smithsonian Center for Astrophysics)
- Ian Garrick-Bethell (UCSC)
- Robert Gershman (NASA JPL)
- Tom Jones (Florida Institute for Human and Machine Cognition)
- Damon Landau (NASA JPL)
- Chris Lewicki (Arkyd Astronautics)
- John Lewis (University of Arizona)
- Pedro Llanos (USC)
- Mark Lupisella (NASA GSFC)
- Dan Mazanek (NASA LaRC)
- Prakhar Mehrotra (Caltech)
- Joe Nuth (NASA GSFC)
- Kevin Parkin (NASA ARC)
- Rusty Schweickart (B612 Foundation)
- Guru Singh (NASA JPL)
- Nathan Strange (NASA JPL)
- Marco Tantardini (The Planetary Society)
- Brian Wilcox (NASA JPL)
- Colin Williams (NASA JPL)
- Willie Williams (NASA JSC)
- Don Yeomans (NASA JPL)

Two Workshops – Sept 2011, Feb 2012

RATIONALE

- **Near human mission target beyond the Moon**
    - **First step on flexible path into the solar system**
    - **Test bed for human exploration operations**



- Asteroid Exploration/ Resource Utilization
    - Water
    - Propellants
    - Materials for radiation shielding
- Science

OUTLINE

1. Objectives
2. Target Identification
3. Destinations and Investigations
4. Flight System and Capture Mechanism
5. Mission and Trajectory Design
6. Mission Benefits
7. COMPASS Study
8. Conclusions
9. Roadmap
10. Follow-up

OBJECTIVES

- Determine the feasibility of robotically capturing and returning a small near-Earth asteroid to the vicinity of the Earth using technology available in this decade.
- Identify the benefits to NASA, the scientific community, the aerospace community, and the general public of such an endeavor.
- Identify how this endeavor could impact NASA's and the international space community's plans for human exploration beyond low-Earth orbit.

TARGET IDENTIFICATION

<u>Determine minimum asteroid size that enables a target discovery and characterization rate to provide candidate NEAs by 2020.</u>

- Larger asteroids easier to discover and characterize but much harder to move.
- Volume and mass scale as the cube of the diameter,
- projected area (and brightness) scales as the square of the diameter

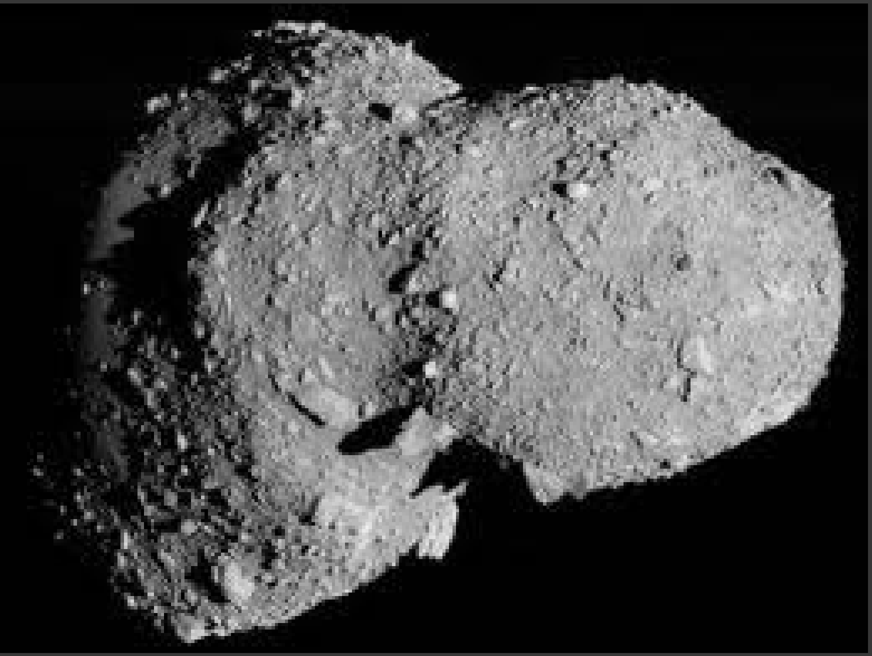
<u>Determine the overlap between NEAs large enough to be discovered and characterized and those small enough to be moved</u>

For each candidate target asteroid need to know:

- **orbit**
- **spectral type**
- **size**
- **shape**
- **spin state**
- **mass**

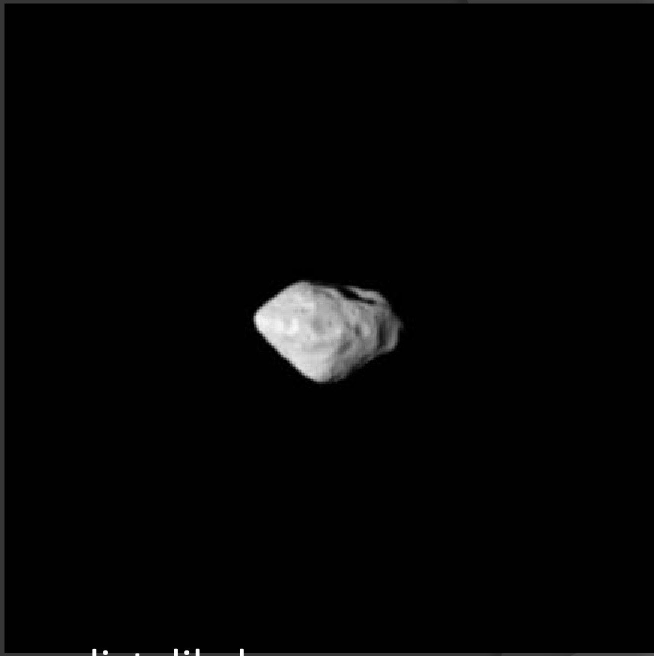
Two Types of Targets

A boulder from a known large asteroid



Part of an asteroid could be perceived as glorified sample return

Find a small asteroid (3-7 m)



Difficult to predict, likely not carbonaceous, random select, but lots of potential targets

Ideal Target: Carbonaceous

Water/ice to make propellants

Heating provides accessible platinum group metals

Asteroid Mass vs Diameter

Diameter (m)	Asteroid Mass (kg)		
	1.9 g/cm^3	2.8 g/cm^3	3.8 g/cm^3
2.0	7,959	11,729	15,917
2.5	15,544	22,907	31,089
3.0	26,861	39,584	53,721
3.5	42,654	62,858	85,307
4.0	63,670	93,829	127,339
4.5	90,655	133,596	181,309
5.0	124,355	183,260	248,709
5.5	165,516	243,918	331,032
6.0	214,885	316,673	429,770
6.5	273,207	402,621	546,415
7.0	341,229	502,864	682,459
7.5	419,697	618,501	839,394
8.0	509,357	750,631	1,018,714
8.5	610,955	900,354	1,221,909
9.0	725,237	1,068,770	1,450,473
9.5	852,949	1,256,977	1,705,898
10.0	994,838	1,466,077	1,989,675

The International Space Station has a mass of 450,000 kg: as a 7-m diameter asteroid

The majority of NEAs have densities between 1.9 g/cm^3 and 3.8 g/cm^3.

Present Knowledge

- ~20,500 NEAs >100 meters: about 25% discovered to date
- Millions of NEAs >10 meters and billions of NEAs >2 meters
  - less than one percent have been discovered
- Small NEAs discovered only during very close Earth approaches
  - however, 280 asteroids approximately 10-m diameter discovered
  - few of these currently have secure orbits
  - none of them have the physical (spectral class, albedos, true diameters…)

Increasing Our Knowledge

Entendu: **product** of the **telescope's aperture** and its **field of view**.

- for Catalina Sky Survey (CSS) entendu is ~ **2**
- for Panoramic Survey Telescope and Rapid Response System 1 (**Pan STARRS 1)** etendu expected to be ~ **13** when fully operational
- for **PanSTARRS 4**, entendu will be ~ **51**
- Large Synoptic Survey Telescope (**LSST**), entendu ~ **320** (planed 2018)

The **number of accessible targets today should increase by two orders of magnitude** when the next generation NEO search telescopes come on line

Target Mass

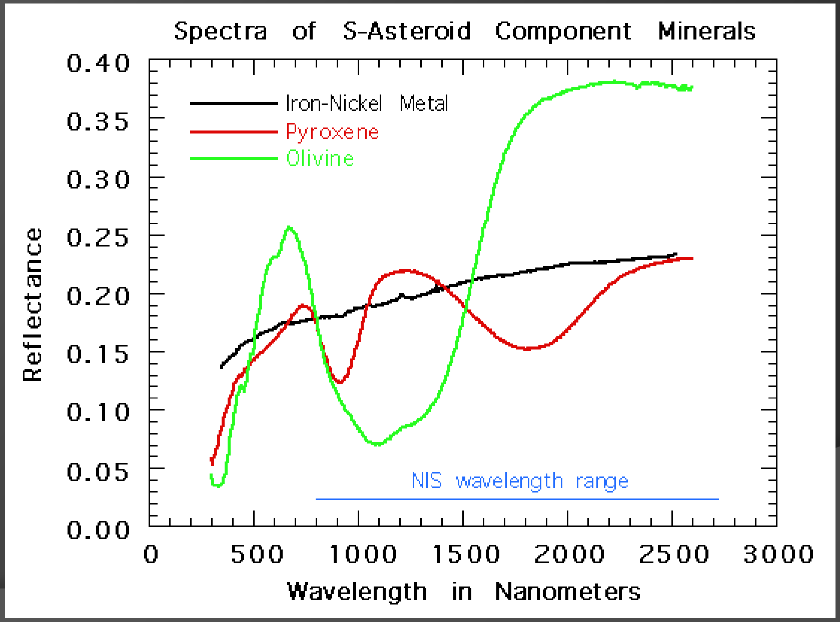
- First knowledge is **orbit and absolute magnitudes**
- Albedo determines diameter from absolute magnitude
    - most NEAs albedos 0.05 - 0.20, yields **diameter** to a **factor of 2**
- The object's **volume** can only be quantified to within a **factor of 8 or 10**

→

- The **mass** of an NEA to within **factor of 20** for objects **without any information beyond the discovery magnitude**
- Estimate asteroid's mass **accurately with** additional data:
    - **follow-up observations must occur** as soon as possible after a potential target is discovered - ideal start within a day

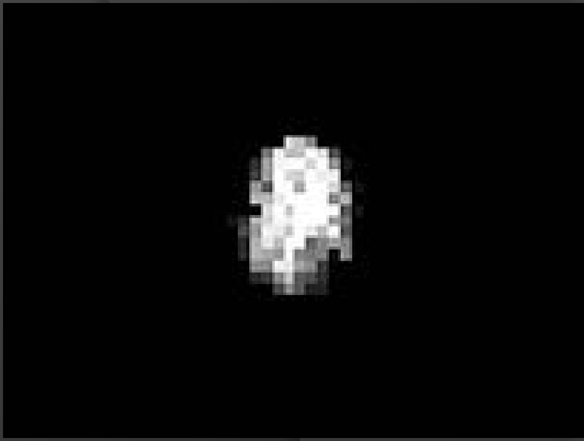
Follow-Up Observations

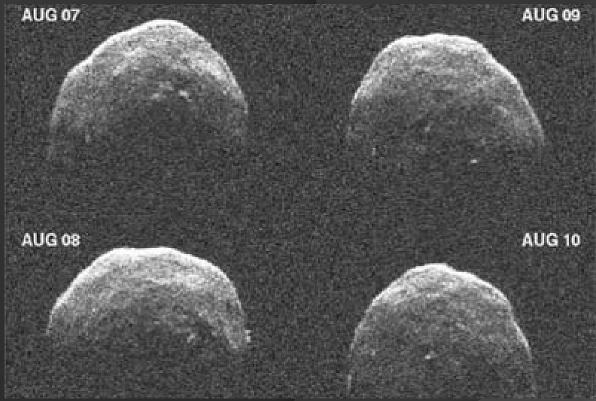
- **Additional optical astrometry** to better determine the NEA's trajectory and ensure that it will not be lost (professional and amateur astronomers)
- **Optical lightcurve measurements** for the object's **spin rate** and if it is in a **tumbling** non-principal-axis rotation state **or not**
- **Optical and near-infrared spectroscopy** for asteroid's **composition**
- **High-sensitivity spectroscopy (optical and near-IR)**: will unambiguously indicate a **carbonaceous chondrite** composition



Additional Measurements Needed

- **Thermal infrared** flux measurements for object’s albedo.
    - For small objects **dimensions** are only accurate to **~30-40%.**
- **Radar ranging measurements** to determine orbit and dimensions
    - Goldstone Radar can image asteroids with resolution 3.75 m.
- With optical astrometry only, require at least two epochs of observation separated by several years to obtain a similar orbit solution.
- With radar imaging, obtain a ~10-m NEA's dimensions to within <=40%, and volume to within a factor of 2.75. With composition information, this yields **uncertainty in the asteroid's mass of a factor of 4 for most objects**.





Actions to Increase Discovery Rate

Goal: **Locate several accessible ~10-m carbonaceous-chondrite objects which could be returned to Earth in the 2020's.**

Increase is possible with minor adjustments in current programs:

- A 10-m asteroid at ~0.03 AU have an apparent magnitude of 18 and be moving at ~1º/hour.
- Both **Pan-STARRS** and **Palomar Transient Factory** (PTF) currently automatically reject such fast-moving objects
  - if the pipelines can be modified to report such detections instead **these two surveys should discover roughly three 10-m objects per night**
- Follow-up observations must be executed in a matter of hours or days.

Target Identification: Conclusions

- Small asteroids only discovered when they make very close approach to Earth
- Synodic periods of approximately one decade for NEAs of interest:
    - enables object to be discovered and characterized followed by a mission targeted to return the NEA by the next close approach ~ 10 years later
- One example: Asteroid 2008HU4 (proof of concept):
    - estimated to be roughly 7-m in diameter and will make its next close approach to Earth in 2016 with a subsequent close approach in 2026
- Alternative approach is to target a larger NEA, knowing it likely a rubble pile to take a 7-m piece off it.
    - if a single right-sized piece cannot be found, then collect enough regolith or many small pieces

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DESTINATIONS AND INVESTIGATIONS

- *<u>What type of asteroid would be most desirable to bring back?</u>*
- *<u>To what final destination should the asteroid be delivered?</u>*
- *<u>What should the asteroid be used for at this location?</u>*

Carbonaceous asteroids are the most compositionally diverse asteroids and contain a rich mixture of **volatiles**, **dry rock**, and **metals**.

- Human mission architecture team has selected EM L2
- Final destination of **Lunar orbit** or outer **Earth-Moon Lagrange point** (**L2** is selected by safety and other mission design factors)

- L2 is also a place at which there is some foreseeable future demand for water and water-derived propellants.

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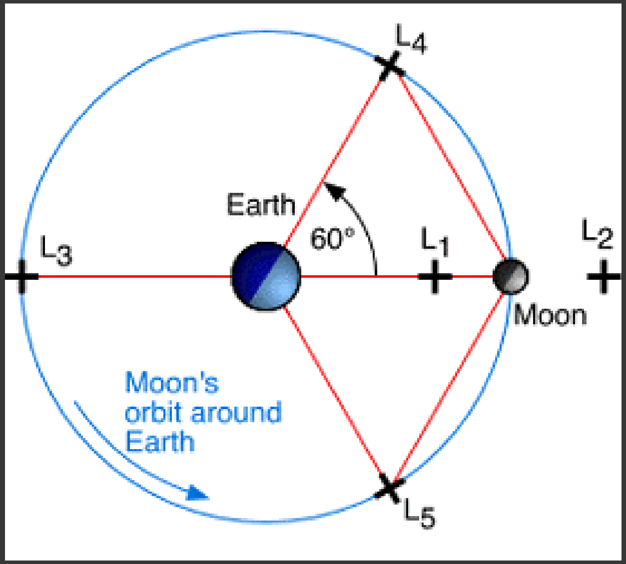
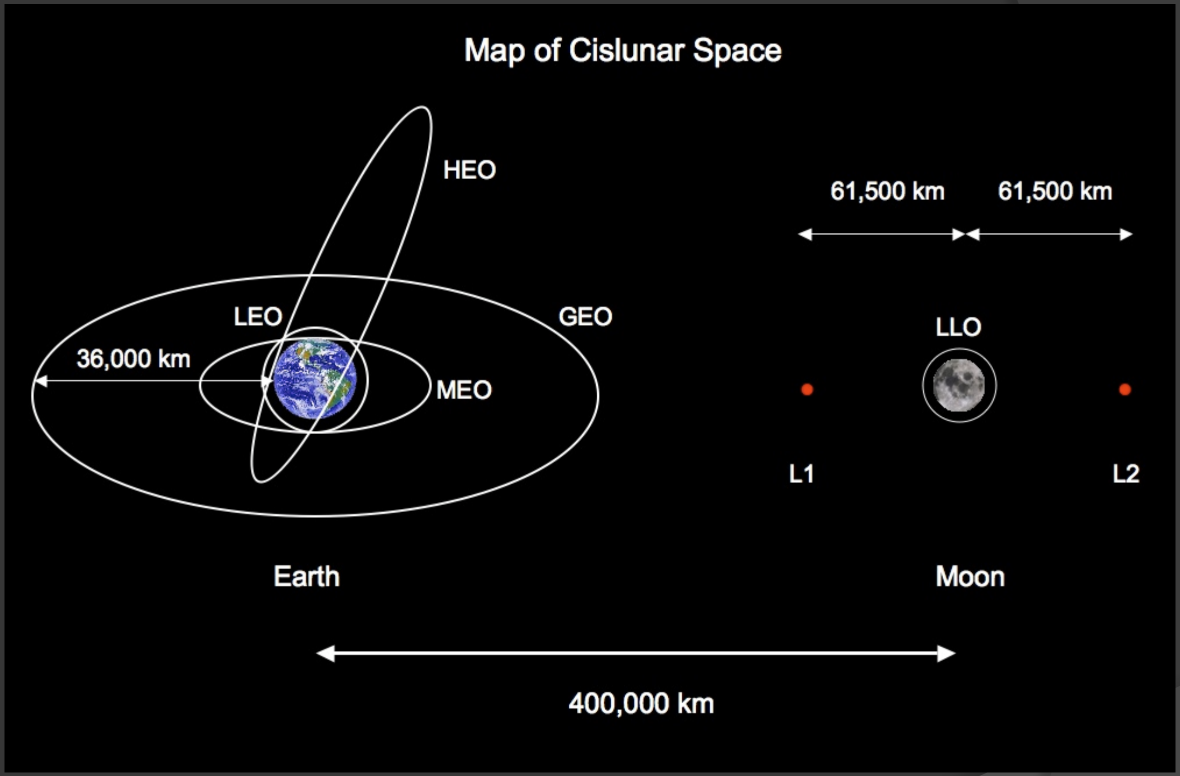
The Earth-Moon L2 Destination





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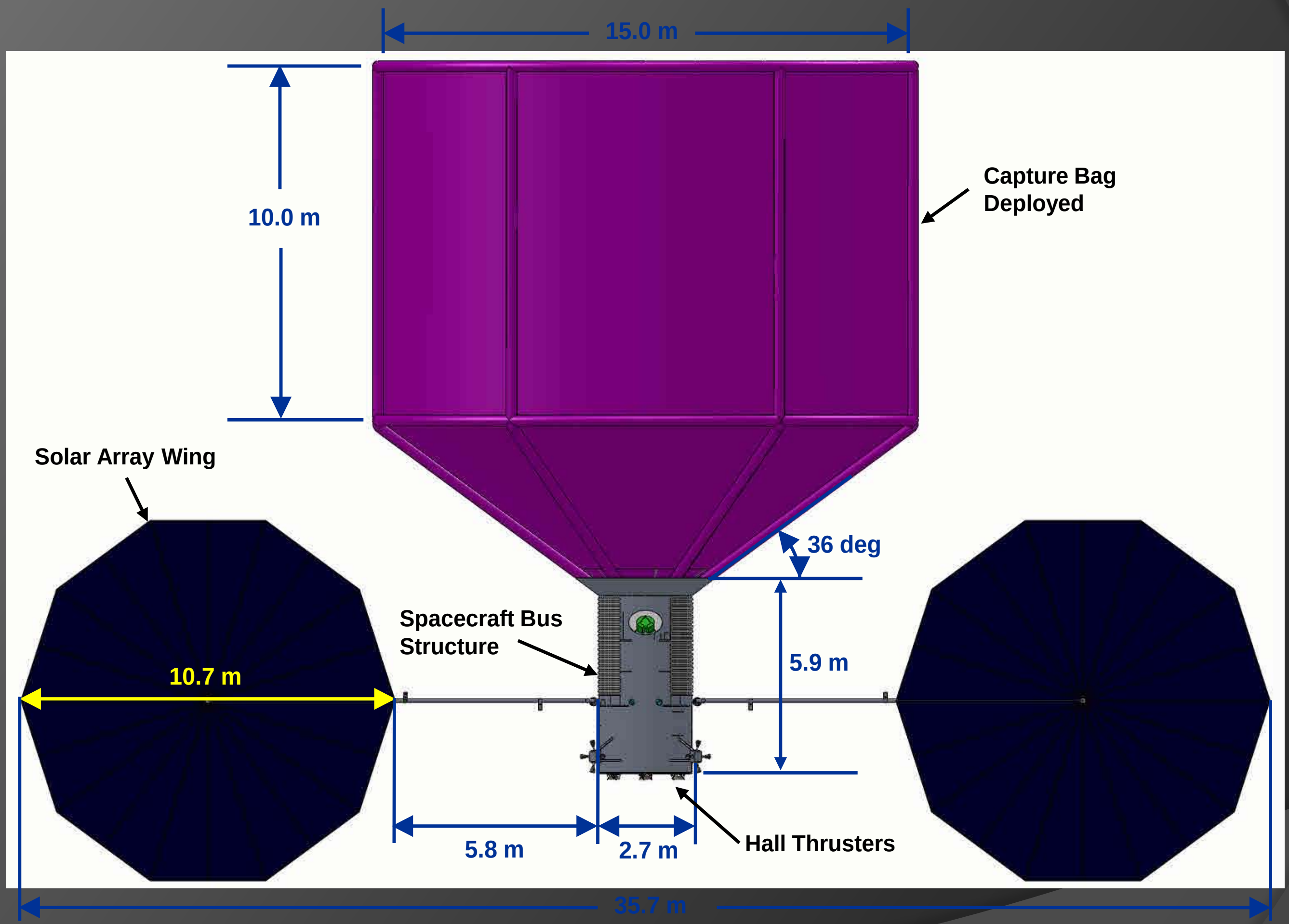
SAFETY

A key issue both in fact and in perception

- Asteroid is meteorite sized, no more dangerous than objects that regularly impact
- The carbonaceous asteroids such that it will break up harmlessly in the Earth's atmosphere
- Spacecraft control ability can move asteroid away from Earth
- Target is stable lunar orbit: instability would lead it to the Moon, not Earth

FLIGHT SYSTEM AND CAPTURE MECHANISM



SOLAR ELECTRIC SPACECRAFT

- **40 kW** (end of life at 1 AU) SEP
- **two** solar panels each of **71 m^2**
- **150 W/kg** available for a launch in 2020
- **Five 10-kW Hall thrusters**
  - 19 kg/thruster
  - specific impulse up to 3000s at thruster input power level of ~10 kW
- Seven **xenon** tanks needed to store the **11,430 kg** of xenon required for this mission - each tank would have a diameter of 650 mm and is 3,500 mm long
- Two flight system architectures considered:
  - **Separable Spacecraft** Architecture
  - **Single Spacecraft** Architecture

Single or Dual Spacecraft Options

Separable Spacecraft - SEP Stage (SS) and NEA capture S/C

-SS provides

- Interplanetary propulsion (outbound and inbound)
- Long-range communications with Earth
- Short-range communications with the S/C
- Post-capture rendezvous with S/C

- Capture S/C provides

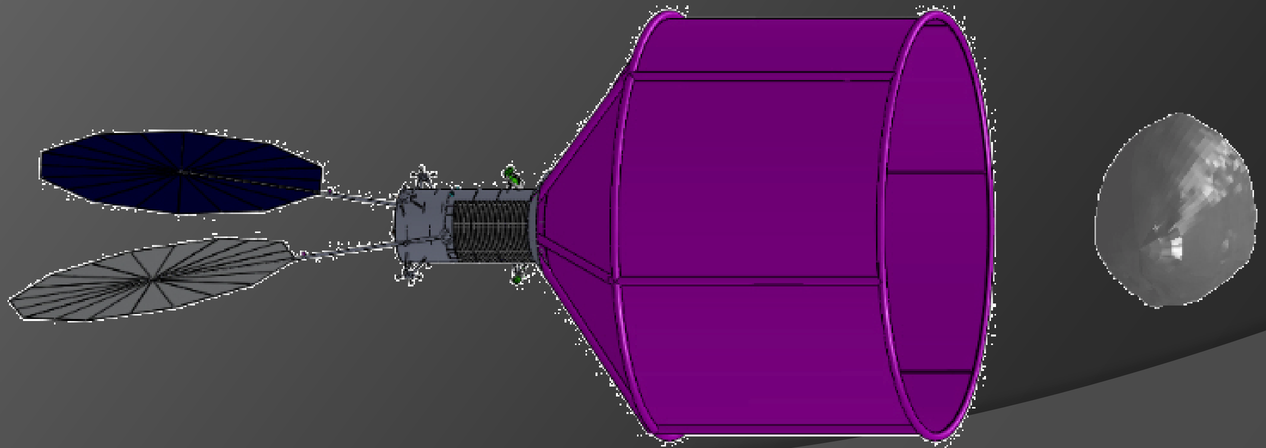
- Capture and de-tumbling of NEA
- Instruments for in-situ characterization of NEA
- cameras to assist in capture

Single Spacecraft

- Characterization and capture functionality included in SEP vehicle
- Studied by GRC's COMPASS team
- Launch Mass = 17,000 kg (12,000 kg Xenon + 900 kg hydrazine)

Pros and Cons of Separable S/C

- Pros
  - Allows smaller, more nimble capture vehicle
  - SEP Stage provide comm relay and remote observation of NEA capture
- Cons
  - Costs assumed to be higher (two vehicles)
  - AR&D with SEP Stage required
  - Limited energy capability on capture S/C

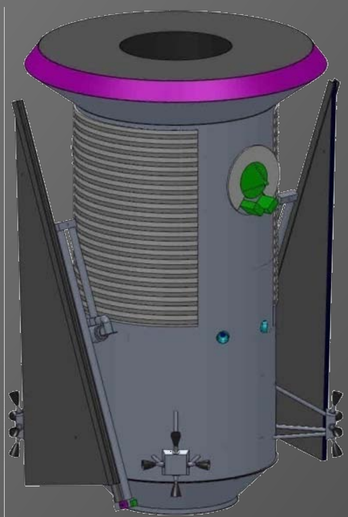


Capturing and De-Spinning a NEA

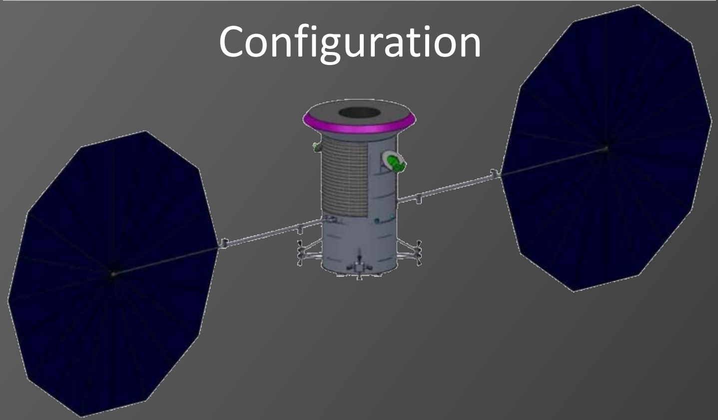
- Using SEP to stop a spinning NEA is simple if it can be grappled effectively
- A 30 kW SEP system can stop a NEA w/ 2-m radius & 10-minute spin period in 1 revolution
- The bag accommodates 1000 cubic meters of sample and must be deployed
- Inflated tube open the bag tubes and the whole assembly is made of fabric and deploys out of a compact package

Earth's gravity	9.81	m/s2
Gravitational contant	6.67E-11	MKS units
Solar flux at 1 AU	1350	W/m2
density of asteroid	2500	kg/m3
spin period	0.16666667	hours
radius	2	m
mass	8.38E+04	kg
moment of inertia	134041.287	MKS units
angular velocity	0.01047198	radians/s
angular momentum	1403.67707	kg*m/s
SEP propulsion		
Power	16,500	W
Isp	3000	seconds
mass flow rate	3.8101E-05	kg/s
thrust	1.12130479	N
torque	2.24260958	Nm
time to thrust	625.912366	seconds
total propellant mass	0.02384772	kg

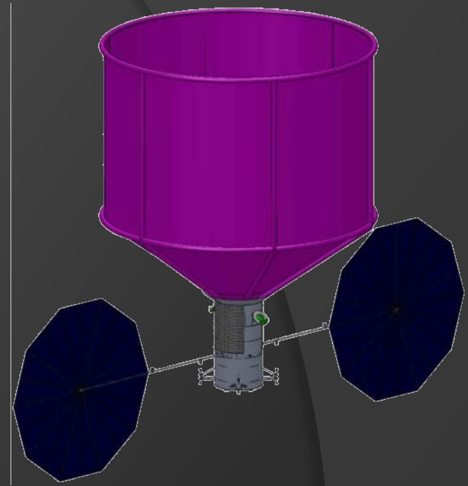
Launch Configuration

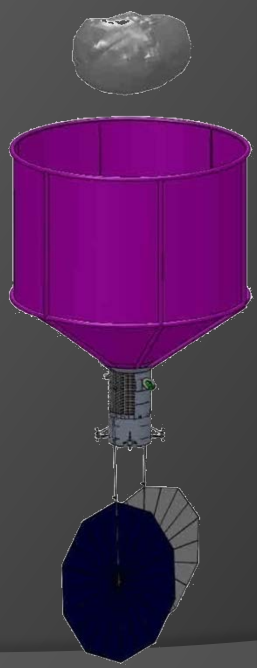


Outbound Transit Configuration

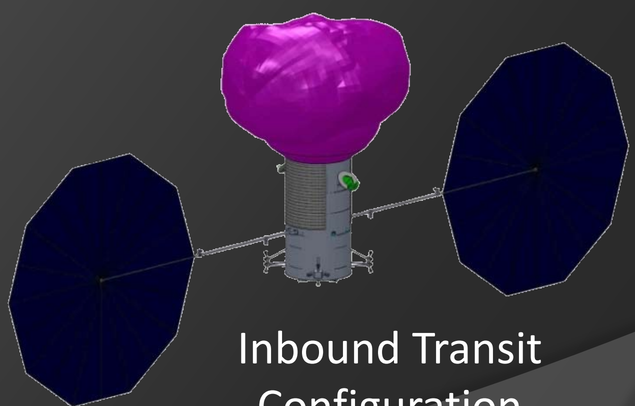


Asteroid Capture Bag Deployed



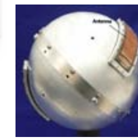
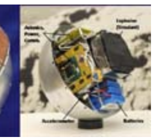


Asteroid Capture Configuration



Inbound Transit Configuration

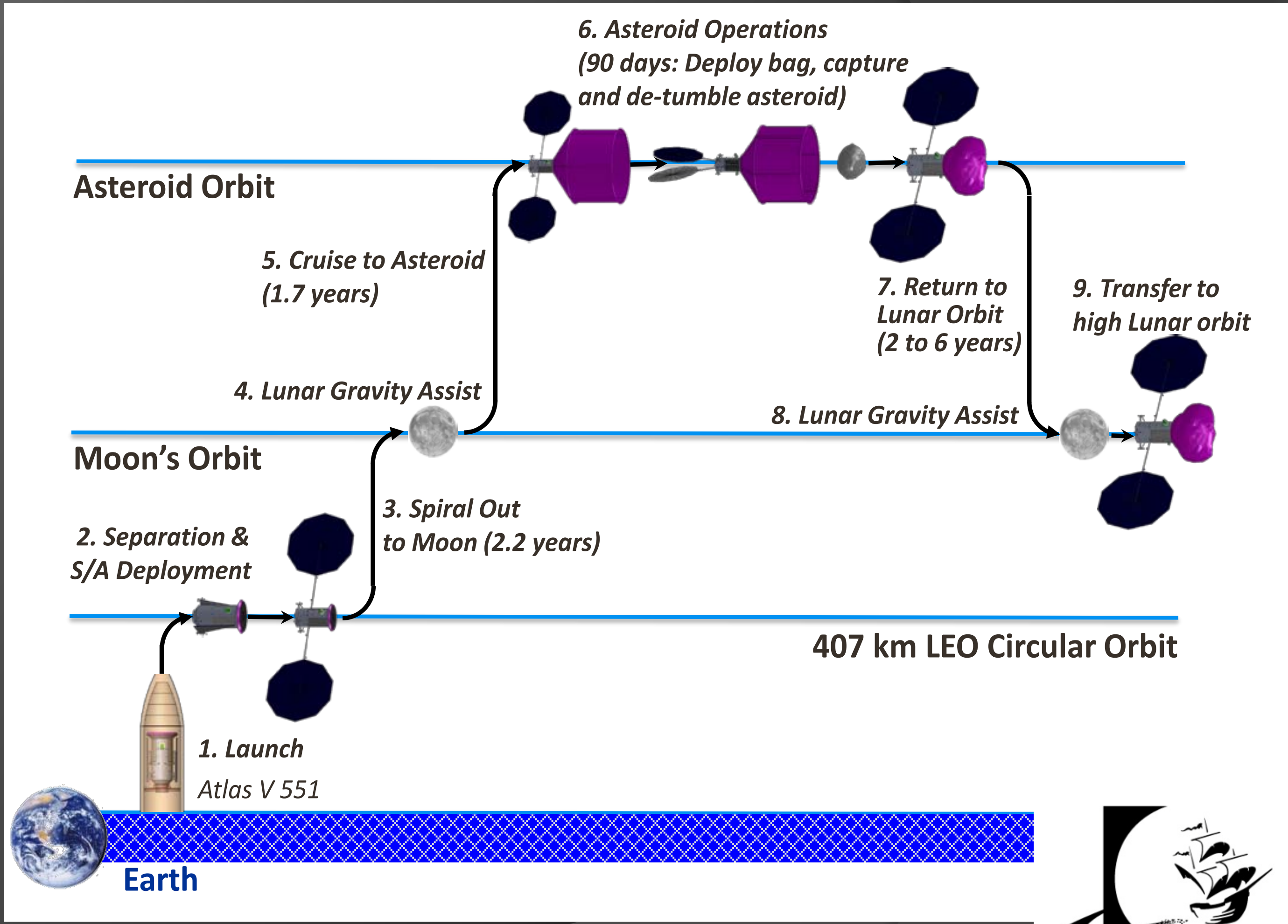
Candidate Instruments

				N/A	  
Parameters	Vis Cam (OpNav)	Vis Cam (ProxOps)	NIR Spec	LIDAR	CubeSat probes; pod
Format/ Heritage	Dawn Camera	Ecliptic	Pushbom M3	3D flash STORRM	3-4 x 1 U; 1-2 x 2 U? 3-axis accels; comm; explosive pod? (BATC)
FOV (deg)	5.5 x 5.5	10 x 10	25 x 1	< 200 mrad	~5 x 5
IFOV	94 μrad	200 μrad	1 mrad	0.2 mrad	100 μrad
Range	0.36-1.05 μm; 7+1 channels	0.45-0.9 μm	0.4-3 μm	1μm < 30 km	RGB
Resolution	<0.1 m @ 1 km	~ 0.2 m @ 1 km	2 m @ 1 km	< 200m @ 1 km	~1 cm @ 50 cm
Mass (kg)	5.5	2	8	20	1 kg/cubesat; 5kg/pod
Power (W)	18	5	10	50	N/A
Telemetry rate	12 Mbits/image	12 Mbits/image	2 Mbits/sample	0.1 Mbits/sample	5 Mbps

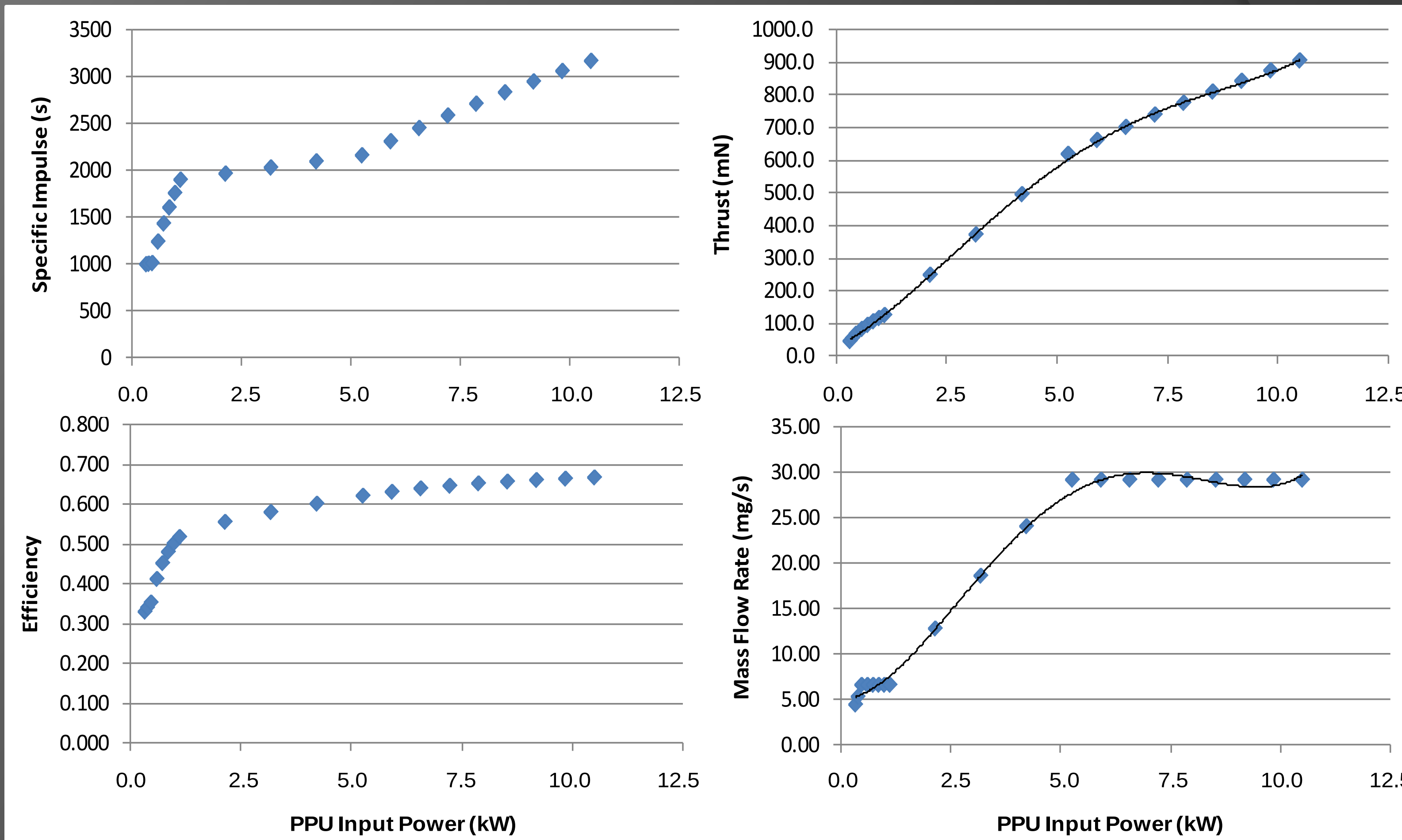
MISSION AND TRAJECTORY DESIGN

Overall mission design assumed launched to LEO on Atlas V 551-class vehicle:

- SEP system spirals to HEO) in 2.2 years
- Lunar gravity assist (LGA) provides C3 >0
- SEP system heliocentric transfer to NEA in 1.7 years
- 90 days assumed at target
- Captured NEA to cis-lunar space into stable high lunar orbit in 2-6 years



SEP System: Performance

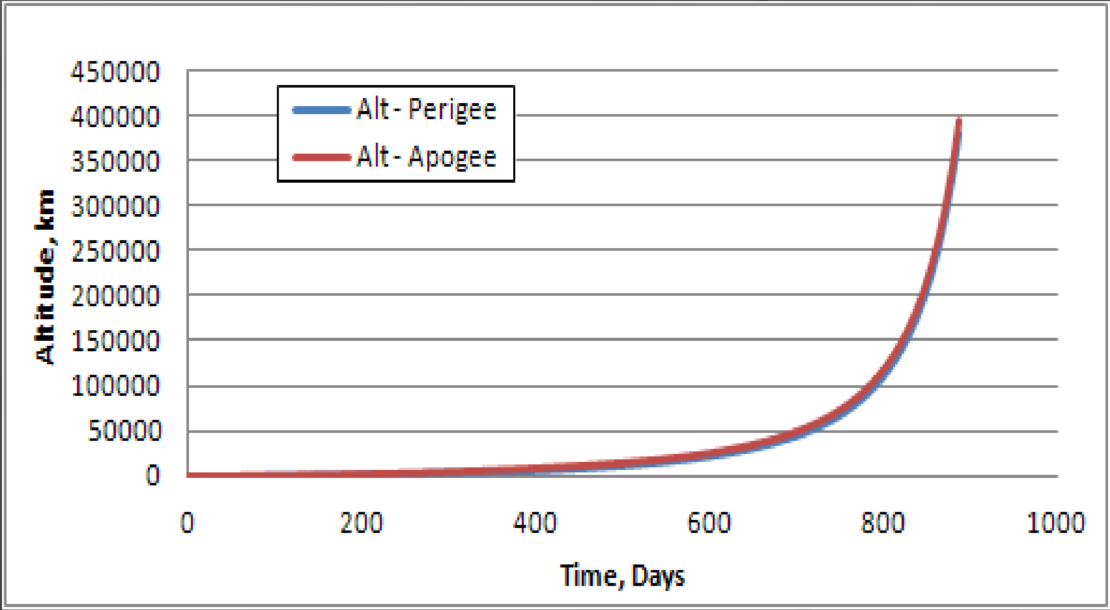


Spiral Out

Trajectory before escape simulated with SNAP (shadowing included)

Duration = 890 days
Total ΔV = 6645m/s

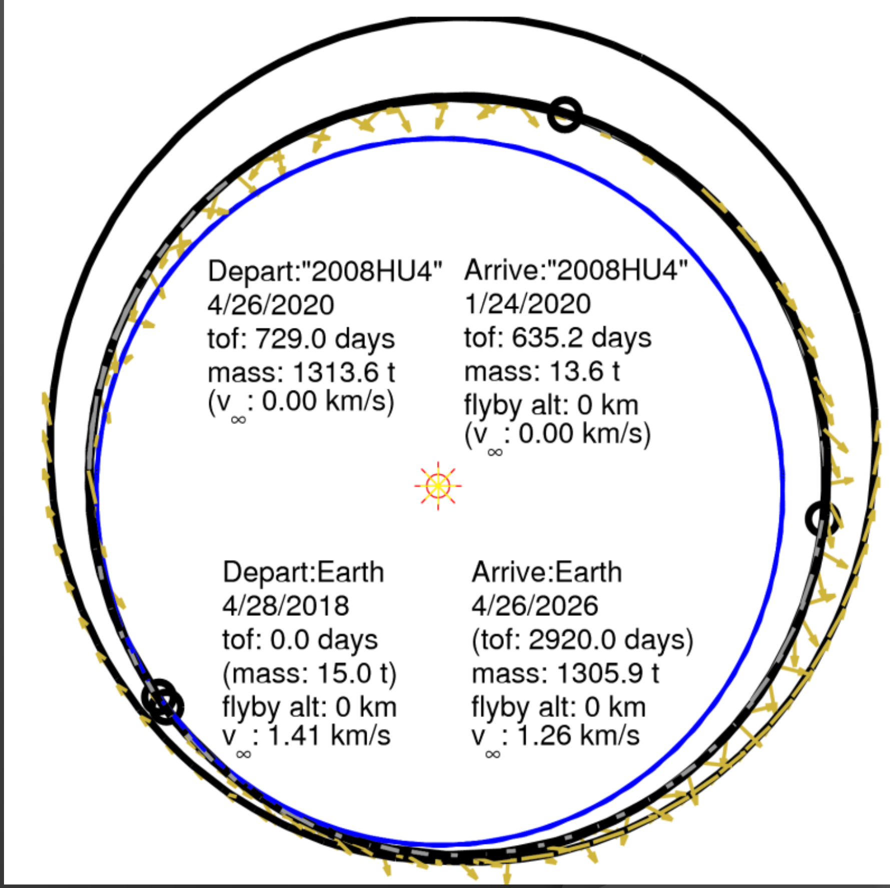
Start mass = 18,800kg
Final mass after LGA = 14,995kg
Propellant prior to LGA = 3,805kg



Proof of Concept Mission -1-

2008 HU4

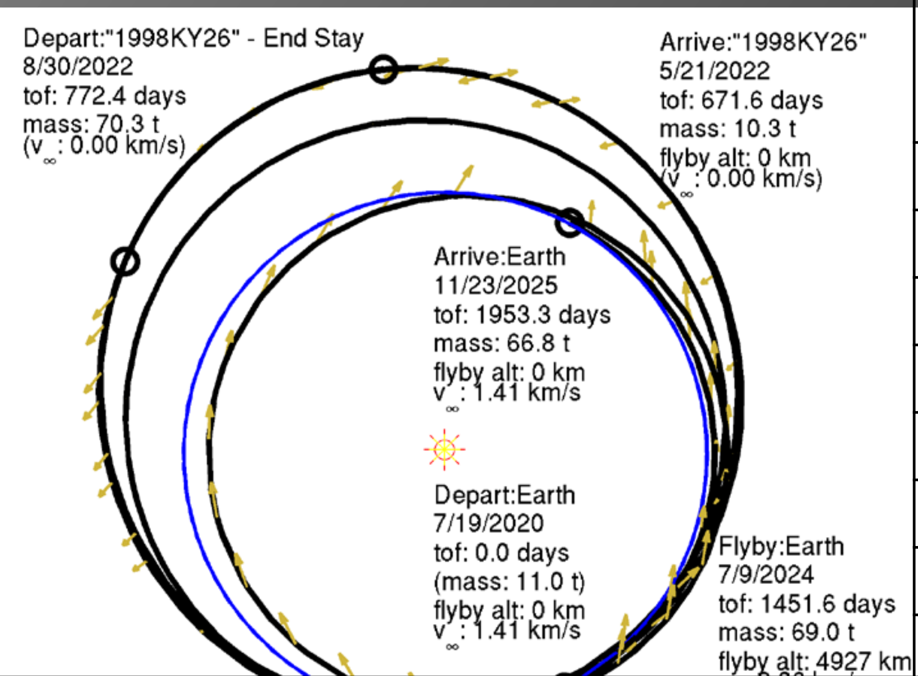
Parameter	Value	Comments
SEP Power	40 kW	
Specific Impulse, *Isp*	3000 s	
EP System Efficiency	60%	
Spacecraft Dry Mass	5.5 t	
Atlas V 521-class LV		
Launch Mass to LEO	13.5 t	
Spiral Time	1.6 years	No shadowing
Spiral Xe Used	2.8 t	
Mass at Earth Escape	10.7 t	
Atlas V 551-class LV		
Launch Mass to LEO	18.8 t	
Spiral Time	2.2 years	
Spiral Xe Used	3.8 t	
Mass at Earth Escape	15.0 t	
Spiral ΔV	6.6 km/s	LEO-intersect Moon
Escape/Capture *C3*	2 km^2/s^2	Lunar assisted
NEA Stay Time	90 days	



- Example mission capturing entire small NEA (~7 m)
- 1300 t returned
- 2008 HU4 has a radar opportunity in 2016

Proof of Concept Mission -2-

1998 KY26

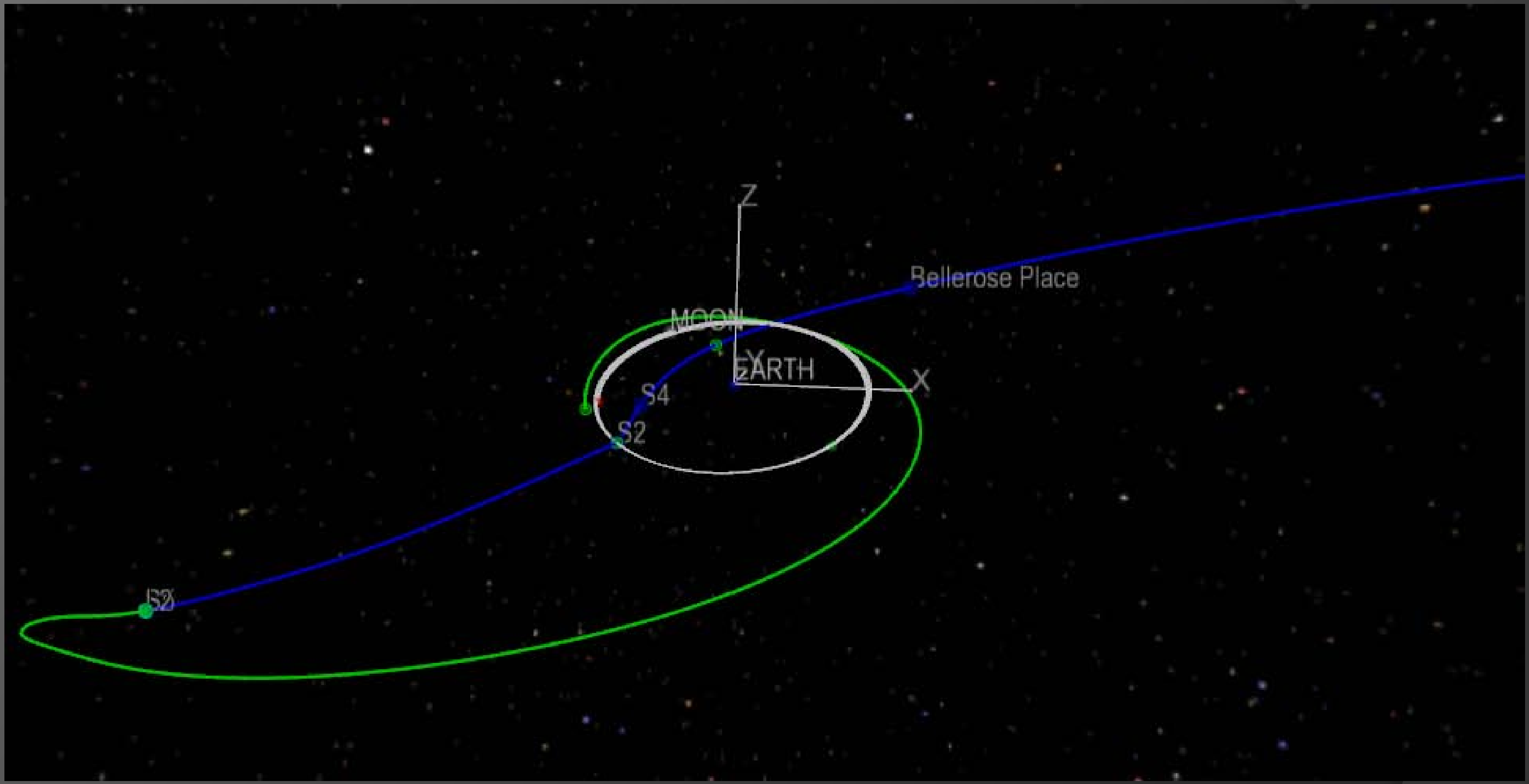


- **Example mission returning part of a well-characterized 30-m carbonaceous NEA**
- **60 t returned**

Designation	Returned Mass, t	Xe, t (no Spiral)	Earth Escape	Flight Time, yr (no spiral)	Arrival C3, km^2/s^2
2008 HU4	250	5.0	4/27/2022	4.0	1.8
2008 HU4	400	5.2	4/27/2021	5.0	1.7
2008 HU4	650	6.5	4/27/2020	6.0	1.6
2008 HU4	950	8.9[a]	4/28/2019	7.0	1.6
2008 HU4	1300	9.1[a]	4/28/2018	8.0	1.6
2008 HU4	200	8.7[a]	8/15/2017	8.0	0.0[b]
1998 KY26	30	4.9	11/11/2019	4.7	2.0
1998 KY26	60	4.2	7/19/2020	5.3	2.0
2000 SG344	1800	1.8	3/8/2027	2.6	2.0
2000 SG344	3600	1.5	2/14/2027	2.6	2.1
2000 SG344	100	6.3	4/20/2024	6.5	0.0[b]

[a]Requires Atlas V (551)-class launch vehicle. All others assume an Atlas V (521)-class launch.
[b]Capture directly to Sun-Earth L2 via a stable manifold. All others assume lunar capture to S-E L2.

Trajectory from Escape to Arrival



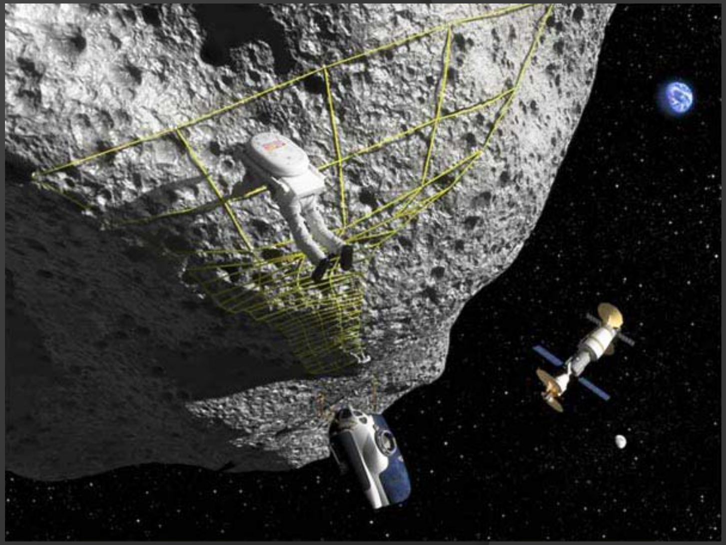
After ~4.5 months from the LGA, the asteroid can be captured into a stable high lunar orbit with 0.0 m/s Δv

MISSION BENEFITS

- Synergy with near-term human exploration
  - provides EM L2 target and operations goal
- Process development for the exploitation of asteroid resources
  - crucial for long-duration space flight
- Synergy with planetary defense
  - demonstrates control and adds to international framework
- Expansion of international cooperation in space
  - advances and broadens human space flight
- Commercial and private interest
  - stimulating new participation

Synergy with Near-term Human Exploration

- First goal beyond the Moon
- Step to interplanetary space and more distant NEAs with longer flights
- Further steps to Phobos, Deimos
- Surface and near by operations prepares humans for future ventures, even to Moon and Mars
    - significant science
    - future utilization of in-space resources



Exploitation of Asteroid Resources

- **Extraction and purification of water**
- **Electrolysis of water into hydrogen and oxygen** and their liquefaction
- ”Baking” to force **autoreduction** of the major **mineral magnetite** (Fe_3O_4) by the carbonaceous polymer, leading to total release of H2O, CO, CO2, N
- **Using released CO** as a reagent for extraction, separation, purification, and fabrication of **iron** and **nickel** products.

Synergy with Planetary Defense

- Moving the asteroid
- Safe planetary defense test
- Test technology
- Greater attention to the planetary defense challenge

Techniques for proximity operations and NEO navigation gained from returning an asteroid would be directly transferable planetary defense planning and implementation.

Expansion of International Cooperation in Space

- Human exploration architecture will be international
- Samples could be returned to Earth for study
- Space-faring nations would have access to the body
- Establish legal and political protocols for altering celestial objects

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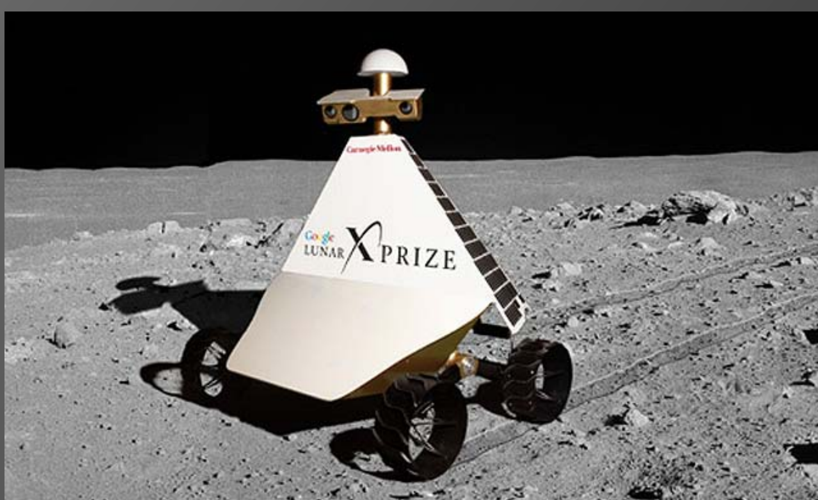
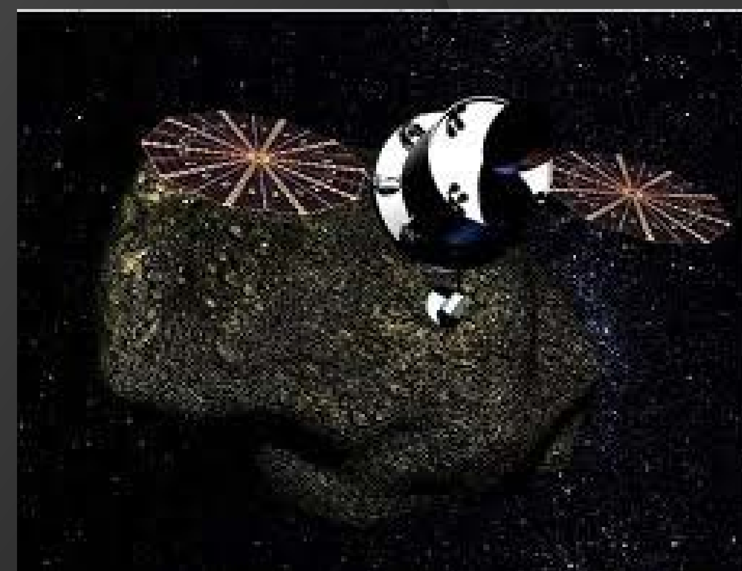
Commercial and Private Interest

- Determination of in-site resource utilization
- Creation of prizes for technical steps





THE PLANETARY SOCIETY

COMPASS STUDY

System and Mission Point Design

Spacecraft Master Equipment List Rack-up (Mass) - Fetch Case1				COMPASS S/C Design	
WBS	Main Subsystems	Basic Mass (kg)	Growth (kg)	Total Mass (kg)	Aggregate Growth (%)
06.1	Fetch - Spacecraft Bus	15028	512	15539	
06.1.2	Avionics	61	14.3	75	23%
06.1.3	Communications and Tracking	62	15.1	77	24%
06.1.4	Guidance, Navigation and Control	21	3.4	24	17%
06.1.5	Electrical Power Subsystem	929	160.8	1090	17%
06.1.6	Thermal Control (Non-Propellant)	316	56.8	372	18%
06.1.7	Structures and Mechanisms	525	94.5	620	18%
06.1.8	Propulsion and Propellant Management	907	98.9	1006	11%
06.1.9	Propellant	11869		11869	
	Spacecraft Adapter (Stays with ELV Stage)	17	0	17	
	Estimated Spacecraft Dry Mass	3141	512	3653	16%
	Estimated Spacecraft Wet Mass	15010	512	15522	
System LeveL Growth Calculations					Total Growth
	Spacecraft Adapter (Stays with ELV Stage)	0		17	
	Dry Mass Desired System Level Growth	3158	948	4106	30%
	Additional Growth (carried at system level)		436		14%
	Total SEP Stage Wet Mass with Growth	15010	948	15958	

NASA Glenn Research Center

COMPASS STUDY
POINT DESIGN ROUGH COST ESTIMATE

	FY12$M	
NASA insight/oversight	204	15% of prime contractor costs
Phase A	68	5% of B/C/D costs
Spacecraft	1359	Prime Contractor B/C/D cost plus fee (10% - less science payload)
Launch Vehicle	288	Atlas 551
Mission Ops/GDS	117	10 year mission plus set-up
Reserves	611	30% reserves
Total	**2647**	

CONCLUSIONS

- Feasible and safe to capture and move entire NEA to cis-lunar space
- Companion NASA study (COMPASS) estimated cost ~$2.6 billion
- Many benefits identified
  - Human first step target beyond the Moon is <u>the</u> rationale
  - This is the only way that humans can actually reach an asteroid by mid-2020s satisfying the Presidential goal
- Discovery and characterization campaign for small NEAs is needed
- C-type, >7 meters with a synodic period of ~ 10 years desired
  - boulder from large known NEA eases observation requirements
- Practical 40 kw SEP system identified
- Safe orbit transfer trajectories identified
- Several capture mechanisms proposed
  - "bag" appears most promising
  - possible design competition for students
- Additional work needed (see follow up)

ROADMAP NEEDS TO BE PLANNED

Beyond the Moon: Stepping into the Solar System	Benefits at Interim Milestone -- Possible Relation to ESA
NEO observation campaign Ground and space based	Science and planetary defense
Move selected NEO to EM L2	Exciting robotic adventure Tech. demo for planetary defense
Human mission to L2	New astronaut distance record Advance human flight capability Prepares the next step to NEO Unique experiment testing ISRU
Robotic precursor to selected NEO	Characterization of human target
Human mission(s) to NEO(s)	New distance, duration records Advance human flight capability Prepares long duration flight Advances space industry, utility
Human missions to Phobos or Deimos	Apollo 8 analogy for Mars Teleoperated exploration of Mars Prepares next step to Mars
Humans to Mars	

FOLLOW-UP

- Follow-up proposals to KISS and NASA
  - exposure to NASA human program required
- NEO Observation campaign
- Capture technology
- Resource Extraction Demonstration
- Mission/system design – incl. trajectories

Program development: international and private possibilities; roadmap -- **Discuss cooperation opportunities with ESA**

- Student completion: Capture schemes
- IAC presentation (1-5 October, Naples)
  - other conference presentations and papers