Asteroid Return Mission (ARM)

2012 workshop report and ongoing study summary

Caltech Keck Institute for Space Studies (KISS)

National Research Council presentation
28 March 2013, Washington, DC

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Asteroid-return mission (ARM) study — *I*

Phase 1: KISS Workshop on the feasibility of an asteroid-capture & return mission

- Completed in early 2012
- Study co-leads from Caltech, JPL, and The Planetary Society
- Broad invitation and participation (17 national/international organizations)
- April 2012 report on the Web

Objectives:

- Assess feasibility of robotic capture and return of a small near-Earth asteroid to a near-Earth orbit, using technology that can mature in this decade.
- Identify potential impacts on NASA and international space community plans for human exploration beyond low-Earth orbit.
- Identify benefits to NASA/aerospace and scientific communities, and to the general public.

http://www.kiss.caltech.edu/study/asteroid/index.html

Asteroid-return mission (ARM) study — *II*

Phase 2: Three-part follow-on and technical-development study

- October 2012 start, on-going
- Three main study components:
  - Observational campaign to search, and develop the technology to find and characterize suitable Near-Earth Asteroids (NEAs)
  - Development of the asteroid capture mechanism (not presented today)
  - In-space concentrating solar-thermal technology (not presented today)

A NASA-sponsored study recently began at JPL on this concept

- The KISS studies and this presentation are independent of the NASA-sponsored JPL effort

http://www.kiss.caltech.edu/study/asteroid/index.html

Why bring an asteroid?

Create:

- An attractive destination for humans that is close-to/beyond the Moon
- A high-value and accessible place for human-exploration operations and experience
- A stepping stone into the Solar System and on a flexible path to Mars

Provide:

- Opportunity for human operational experience beyond the Moon
- Robotic spacecraft retrieval of valuable resources for human, robotic, and human-robotic synergistic exploration, and potential utilization of material already in space
- Science, technology, and engineering elements relevant to planetary defense

Within current/known constraints, it's a way for humans to reach an asteroid by the mid-2020s.

Bringing a (small) asteroid — *Guidelines*

Small size:

- $d_{ast} \sim 5 - 7$ m, $m_{ast} \lesssim 750$ tons $\pm$; low Earth-frame speed ($u_{ast,i} \lesssim 2.6$ km/s)

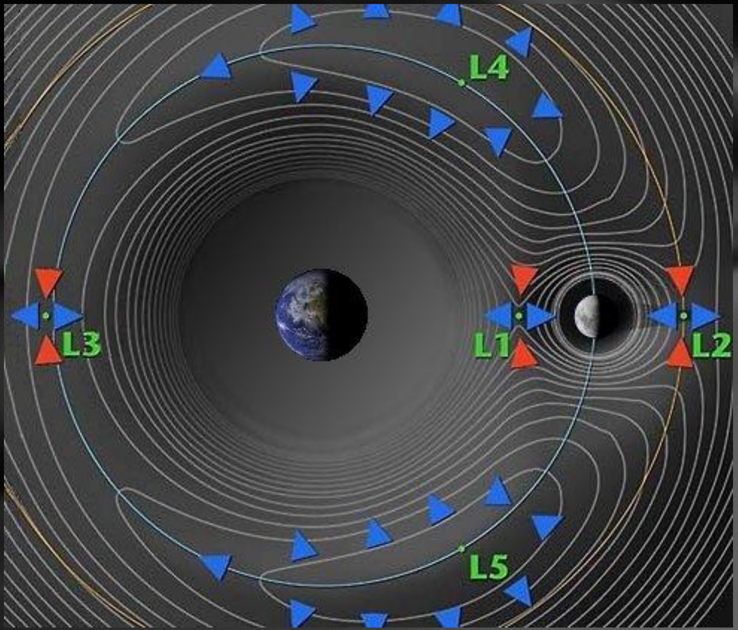
Composition:

- Carbonaceous (C-type), density/strength of "dried mud"
- A rubble pile would break up

Spacecraft trajectory/control

Stable destination orbit:

- E-M L2, high lunar orbit, or other stable orbit



These guidelines coincide with safety:

- Required trajectory coincides with a non-collision course
- Desired asteroid would burn-up high in Earth's atmosphere, should it enter
- Chelyabinsk reference: $d_{Ch,i} \sim 15 - 17$ m, $m_{Ch,i} \cong 11{,}000$ tons; $u_{Ch,i} \cong 19$ km/s

Image credit: http://ccar.colorado.edu/asen5050/projects/projects_2012/wolma/img/earth_moon_l_pts.jpg

ARM perspective

Apollo program returned ~ 400 kg of moon rocks, over six missions.

OSIRIS-REx mission plans to return ~ 0.06 kg of surface material from a B-type near-Earth asteroid (NEA) by 2023.

This study is evaluating the feasibility of returning an entire $\sim$7m NEA, with a mass $\sim 5 \times 10^5$ kg $\pm$, to either L2 or a high lunar orbit, by 2026.

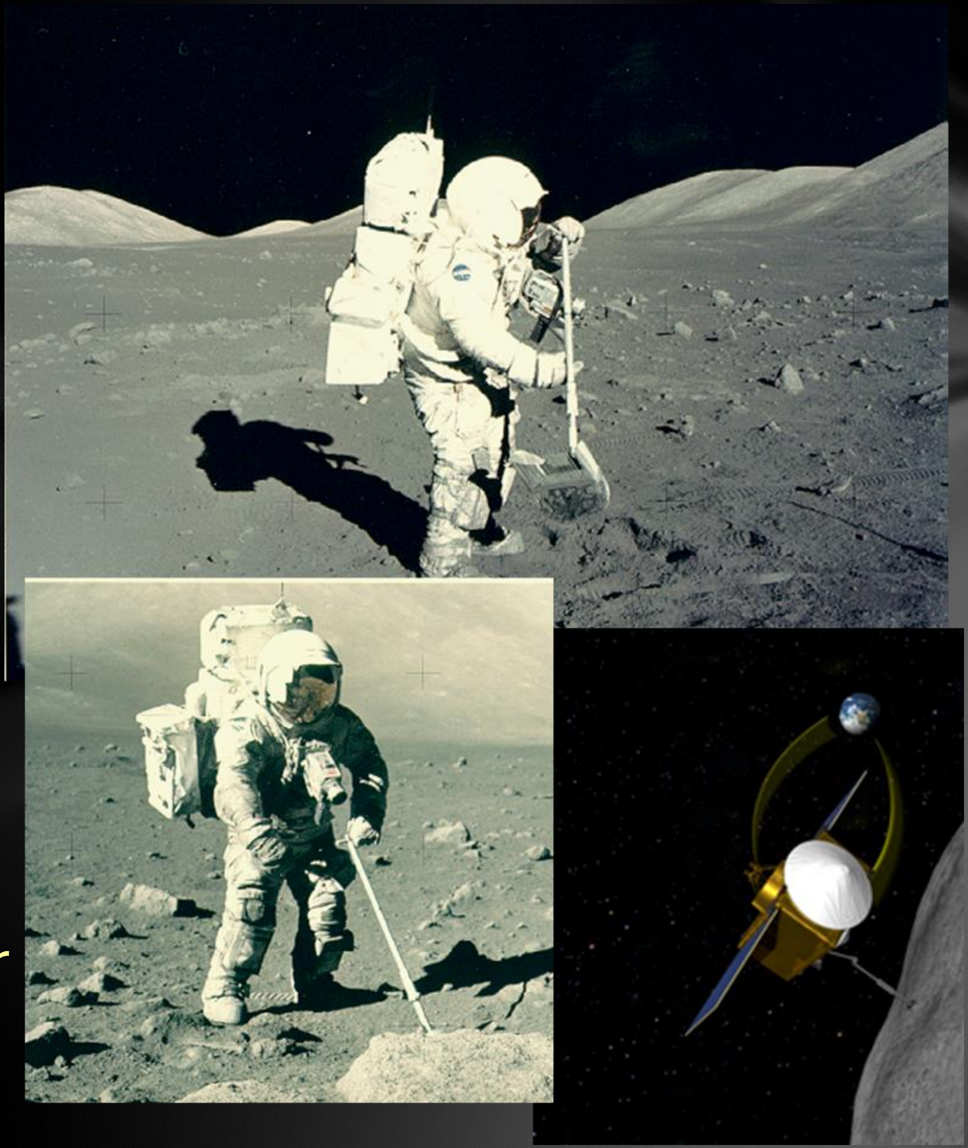
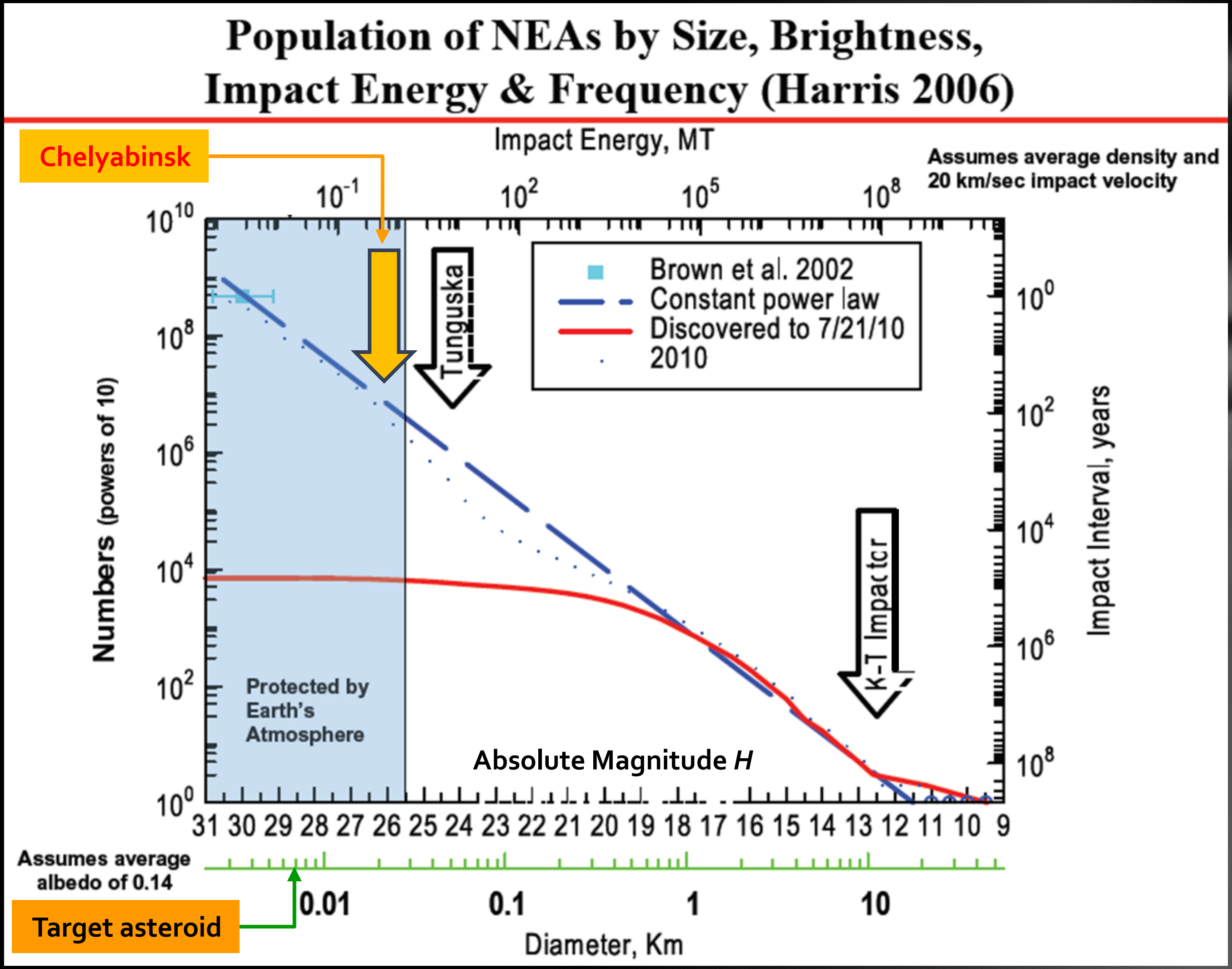


Image credits: NASA Apollo and OSIRIS-REx mission

Target asteroids — *I*



Target asteroids — *II*

Target mass: $m_{ast} \sim 500$ tons ±

- Max : $m_{ast} \sim 1000$ tons
- Density uncertainty: most NEA densities are in the range
  $1.9 \lesssim \rho_{ast} \lesssim 3.9\ \mathrm{g/cm^3}$
- For reference: $m_{ISS} \sim 500$ tons

Prelim. spin rate: $\lesssim 10$ rph

Imparted $\Delta V \lesssim 0.2$ km/s

- Max $\Delta V \sim 2.6$ km/s with lunar-g assist
- Depends on target-asteroid mass

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

Must identify enough candidates that meet requirements to plan a robust mission

For candidate asteroid, we need to know:

- Orbit, spectral type (C-type), size, shape, spin state, mass, and synodic period
- Uncertainties must be small enough to enable flight-system development

Table from Brophy *et al*. 2012 Asteroid Retrieval Feasibility. KISS final report.

Finding target asteroids — *Current status*

Present surveys:

- Relatively complete down to 1km
- Numerous detections down to 100m
- Poor knowledge of population down to 10m

Small number of plausible ARM candidates identified, e.g., 2009 BD, based on magnitude and orbit

- Present NEO detection rate: ~ 1000 /year
- Present ARM candidate rate: $2 - 3$/year*
  - Discoveries are mostly serendipitous

Catalina Sky Survey

No "gold-plated" ARM candidates (suitable orbit, known size, spin, composition) presently known

Observations are mostly ground-based optical

- Some space IR opportunities, e.g., NEOWISE, Spitzer

*** V_∞ test, size-type screening, spin, 2020-25 Earth close approach, … ($\leq 1\%$ suitable for ARM).**

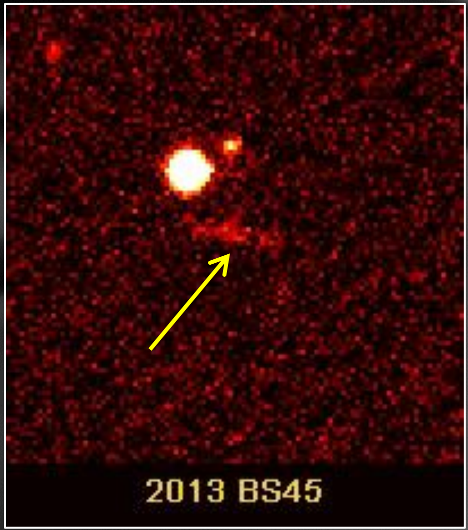
Finding target asteroids - *The challenge*

Very dim: 10m object is 100's of times fainter than a 100m object (5 magnitudes)

- Must be detected close to Earth

Large angular rate ("trailed" on images), only visible for small number of nights (~10) for ground-based surveys

Detection requires large field of view and large apertures (typically > 1m)



**2013 BS45 "flight accessible"
Palomar Transient Factory (PTF)**

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Observational campaign — *What's needed*

Increase NEO discovery rate to ~10/day

Yield: ~5 good targets per year (right size, type, spin state, and orbital characteristics)

Rapid follow-on with a suite of facilities:

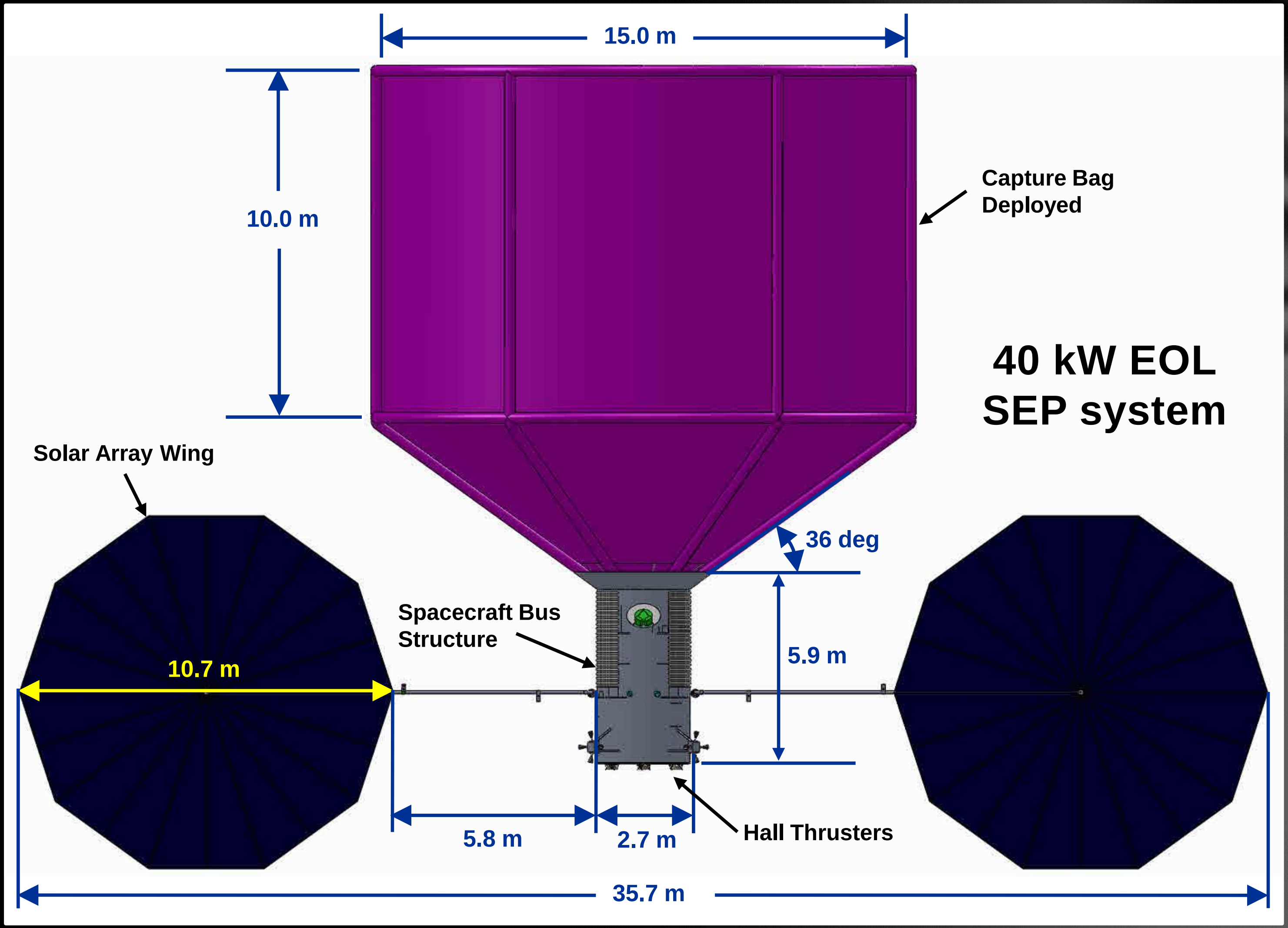
- Refined astrometry (orbit), multi-band photometry (colors), time-resolved photometry (light curves), spectroscopy (C-type or not), radar (size, density, spin), thermal IR (mass/area)

Decrease uncertainties

Time since discovery	Rate (#/day)	Follow-up observation
< 12 hrs	10	Astrometry
< 24 hrs	0.5	Additional astrometry, colors
< 48 hrs	0.2	Light curves
< 48 hrs	0.1	Spectroscopy
< 72 hrs	0.06	Radar

Table derived from Brophy *et al*. 2012 Asteroid Retrieval Feasibility. KISS final report.

Asteroid Capture and Return (ACR) spacecraft



Conceptual flight-system design by the NASA/GRC COMPASS team, with guidance by the KISS team (Brophy *et al*. 2012 Asteroid Retrieval Feasibility. KISS final report).

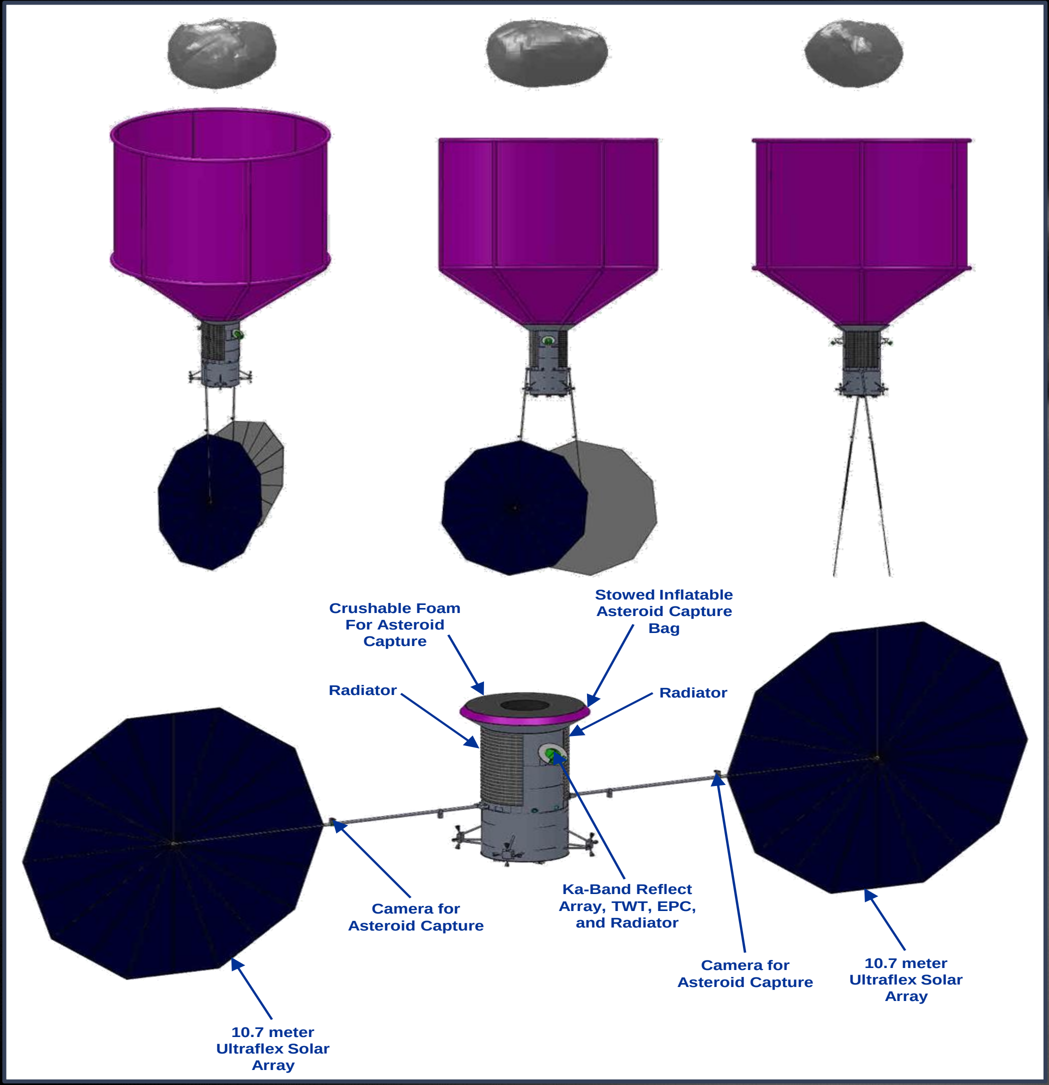
Conceptual ACR spacecraft — *II*

Top:

- Solar arrays folded back to facilitate matching the asteroid spin state during the capture process

Bottom:

- Conceptual ACR flight system configuration before capture-mechanism deployment
- Shows camera locations on solar array yokes used to verify proper deployment and subsequently aid in asteroid capture



Conceptual flight-system design by the NASA/GRC COMPASS team, with guidance by the KISS team (Brophy *et al*. 2012 Asteroid Retrieval Feasibility. KISS final report).

Conceptual ACR spacecraft — *III*
Master Equipment List (MEL)

WBS Number	Description FETCH - October 2011 (CD-2011-67)	QTY	Unit Mass (kg)	Basic Mass (kg)	Growth (%)	Growth (kg)	Predicted Mass (kg)
06	**FETCH - Asteroid Return Spacecraft**			15027.6		511.6	15539.2
06.1	**FETCH - Spacecraft Bus**			15027.6		511.6	15539.2
06.1.1	Payloads			339.0	20.0%	67.8	406.8
06.1.1.a	Main Instruments			339.0	20.0%	67.8	406.8
06.1.2	Avionics			60.9	23.5%	14.3	75.2
06.1.2.a	Command & Data Handling (C&DH)			49.9	22.4%	11.2	61.1
06.1.2.b	Instrumentation & Wiring			11.0	28.2%	3.1	14.1
06.1.3	Communications and Tracking			61.8	24.4%	15.1	76.9
06.1.3.a	Ka-band Reflect Array			46.5	22.5%	10.5	57.0
06.1.3.d	X-band command and safing system			15.3	30.0%	4.6	19.9
06.1.4	Guidance, Navigation, and Control (GN&C)			20.5	16.5%	3.4	23.9
06.1.5	Electrical Power Subsystem			928.8	17.3%	160.8	1089.6
06.1.5.a	Solar Arrays			742.8	15.0%	111.4	854.2
06.1.5.b	Power Cable and Harness Subsystem (C and HS)			60.0	50.0%	30.0	90.0
06.1.5.c	Power Management & Distribution			104.6	15.5%	16.2	120.8
06.1.5.d	Battery System			21.4	15.0%	3.2	24.6
06.1.6	Thermal Control (Non-Propellant)			315.6	18.0%	56.8	372.4
06.1.6.a	Active Thermal Control			4.9	18.0%	0.9	5.7
06.1.6.b	Passive Thermal Control			239.4	18.0%	43.1	282.5
06.1.6.c	Semi-Passive Thermal Control			71.4	18.0%	12.8	84.2
06.1.7	Structures and Mechanisms			525.1	18.0%	94.5	619.7
06.1.7.a	Structures			386.8	18.0%	69.6	456.5
06.1.7.b	Mechanisms			138.3	18.0%	24.9	163.2
06.1.8	Propulsion System			906.7	10.9%	98.9	1005.6
06.1.8.a	Propulsion Hardware (EP)			114.0	14.1%	16.0	130.0
06.1.8.b	Propellant Management (EP)			465.3	11.9%	55.3	520.6
06.1.8.c	Power Processing Unit (PPU)			160.0	12.4%	19.8	179.8
06.1.8.d	Reaction Control System Hardware			167.4	4.6%	7.8	175.2
06.1.9	Propellant			11869.2	0.0%	0.0	11869.2
06.1.9.a	Propellant (EP)			10958.3	0.0%	0.0	10958.3
06.1.9.b	Pressurant			34.3	0.0%	0.0	34.3
06.1.9.c	RCS Propellant			876.6	0.0%	0.0	876.6

Launch vehicle capability to LEO: 18,000 kg

Conceptual flight-system design by the NASA/GRC COMPASS team, with guidance by the KISS team (Brophy *et al*. 2012 Asteroid Retrieval Feasibility. KISS final report).

Solar Electric Propulsion

Envisaged ACR propulsion:

- Solar power: 40 kW (EOL), 50 kW (BOL)
- Hall thrusters: 4 thrusters, 10 kW each, operating in parallel
- Consistent with current NASA Solar Array System (SAS) contract objectives: $30 - 50$ kW range
- Xenon mass: $m_{\mathrm{Xe}} \leq 13$ tons at launch
- Specific impulse: $I_{\mathrm{sp}} \sim 3000$ s
- Thrust level: $T = 1.5$ N
  - Adequate for ≤ 1300 ton favorable-orbit asteroid return
- Assessed as the lowest-risk ARM-propulsion option today

Dawn, for reference:

- Solar power: 10 kW solar array (BOL, 1 AU)
- EP power: 2.5 kW
- Xenon mass: $m_{\mathrm{Xe}} \sim 0.425$ tons at launch
- SEP cost: \$1M/kW for the solar arrays

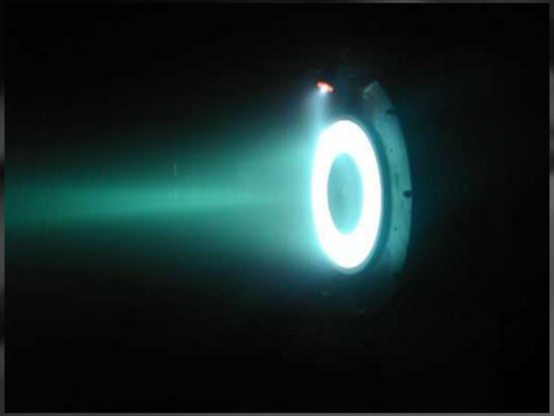


Image credit: http://htx.pppl.gov

SEP is assessed to be an enabling technology for ARM

Proof-of-concept trajectory — *2008 HU4*

Heliocentric frame

- Indicated 'tof' times begin with the completion of a ~ 2.2 year spiral-out Earth-escape phase.

Initial launch mass:

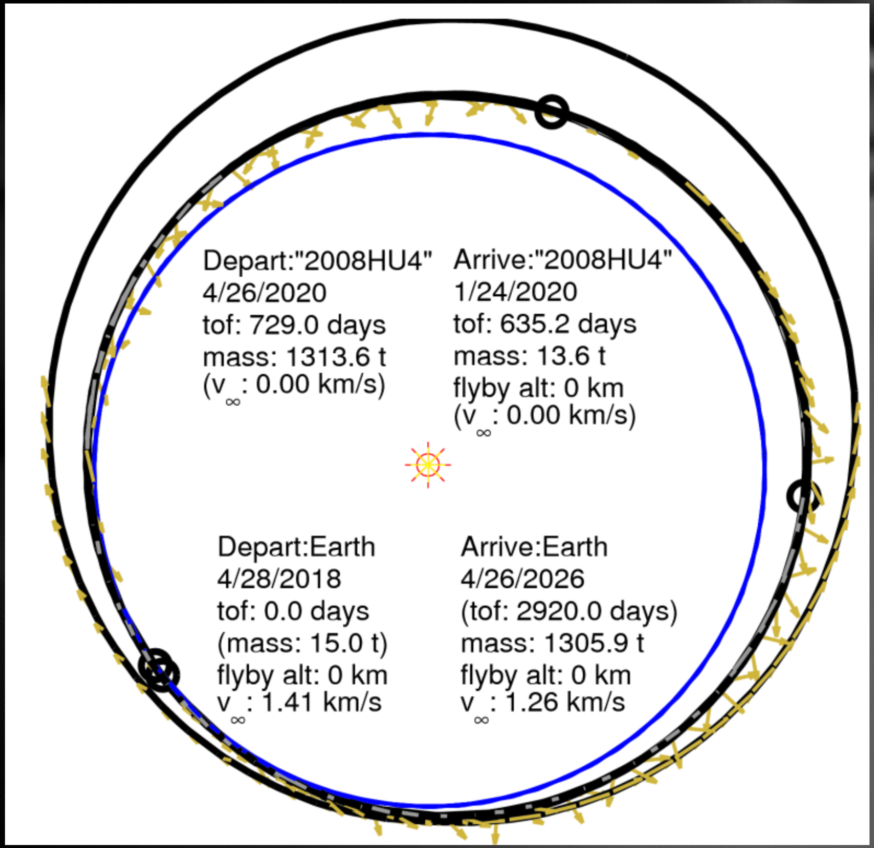
$m_\mathrm{i} \sim 18$ tons

Return mass: $m_\mathrm{r} \sim 1300$ tons

Mass amplification: $\frac{m_\mathrm{r}}{m_\mathrm{i}} > 70:1$

Total flight time: $\tau_\mathrm{f} \sim 10$ years

- Return time fixed by asteroid orbit
- Target asteroid mass uncertainty translates into launch-mass and launch date (tof) uncertainty



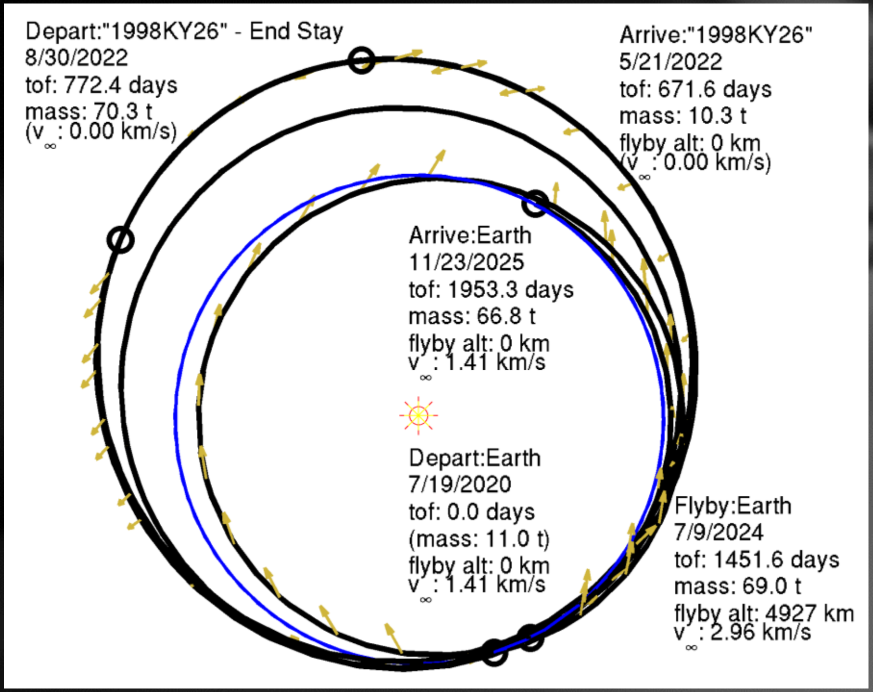
From Brophy *et al*. 2012 Asteroid Retrieval Feasibility. KISS final report.

Proof-of-concept trajectory — *1998 KY26*

Mission options depend on target asteroid characteristics

Alternate: "Boulder" option

- Carbonaceous 1998 KY26
- Initial launch mass: 18 tons
- Return mass: 60 tons (~4 m)
- Whole 1998 KY26 too big to return
- Period/orbit: 500 days
  0.98 × 1.5 AU
- Total flight time: 5.3 years
- Mass amplification: 3.5: 1



Identification of optimal targets and uncertainty reduction (mass, +) is crucial to ARM

From Brophy *et al*. 2012 Asteroid Retrieval Feasibility. KISS final report.

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Proof-of-concept trajectory — *2009 BD*

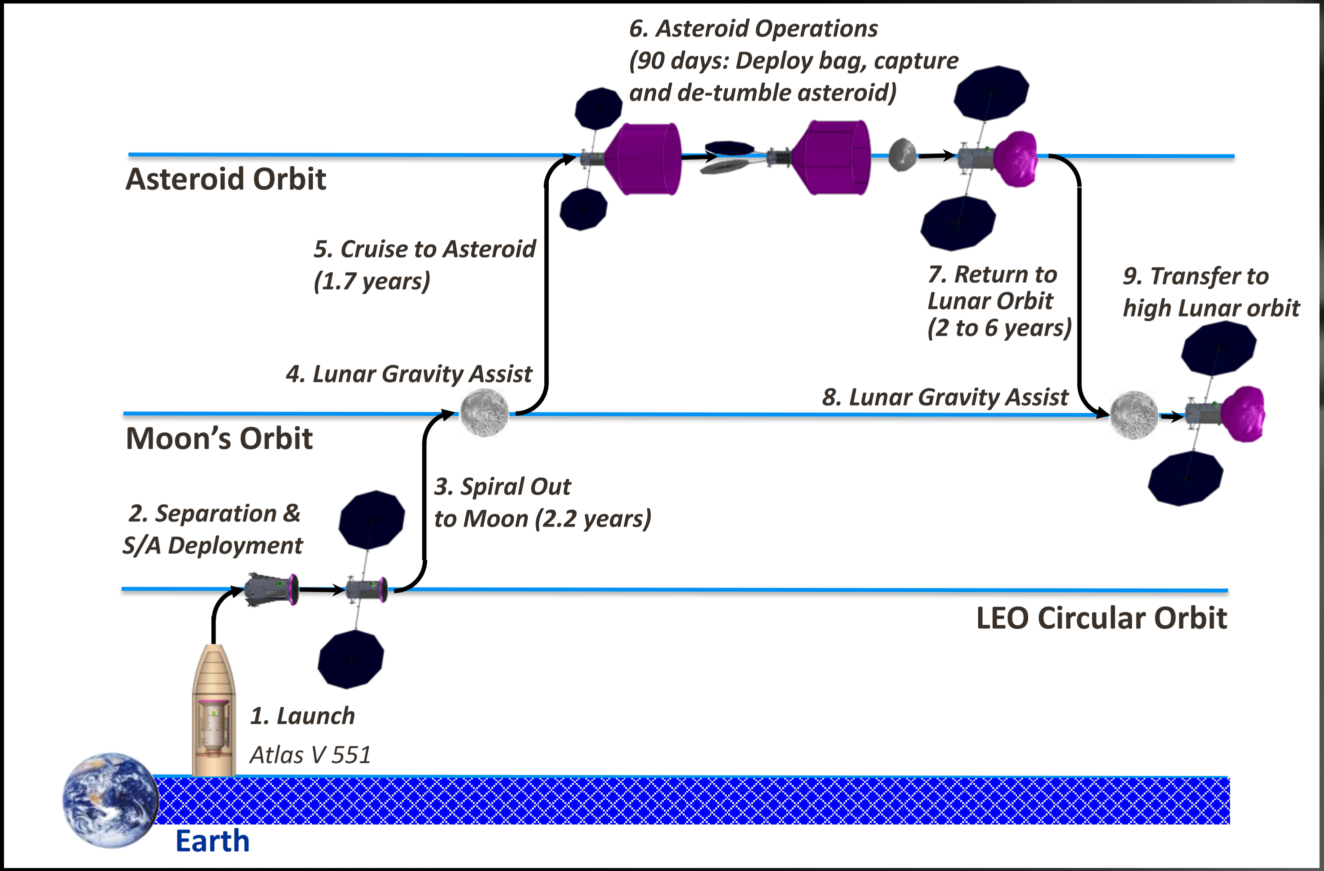
Trajectory illustration for an alternate target

Geocentric/sun-up reference frame

- Earth-centered radial-tangential-normal (RTN) frame
- No wonder the ancients had trouble

Computer-animation credit: Nathan Strange, NASA/Caltech-JPL

Mission description



Brophy *et al*. 2012 Asteroid Retrieval Feasibility. KISS final report.

Mission-destination options

Earth-Moon L2 or High Lunar Orbit

Orbit stability may favor latter

Halo orbit around L2 is also under study

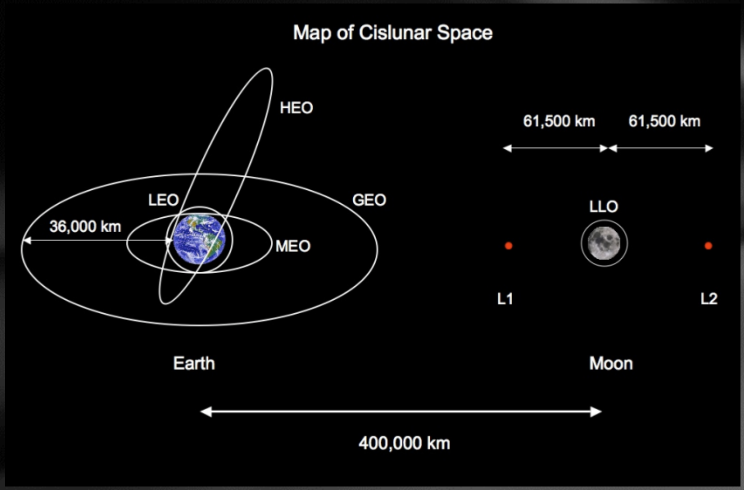
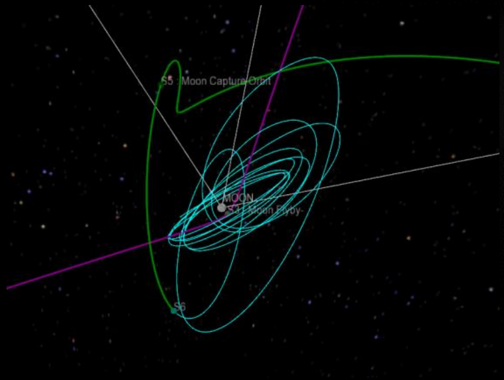
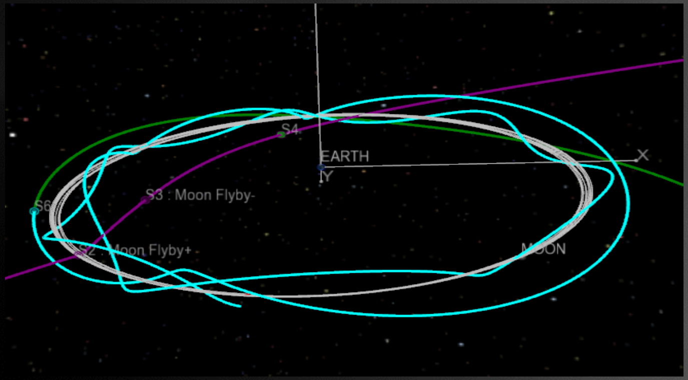


Image credit: www.spudislunarresources.com





Lower figures from Brophy *et al*. 2012 Asteroid Retrieval Feasibility. KISS final report.

Planet safety

Multiple and independent safety layers and factors

- A $7\ \mathrm{m}$ diameter asteroid is too small to be considered a potentially hazardous asteroid (PHA)
  - Will not survive entry
- Low mass and approach velocity
  - Earth entry (initial) energy would be much lower than the Chelyabinsk meteor's:

$$E_{\mathrm{e}} = \frac{1}{2} m_{\mathrm{e}} U_{\mathrm{e}}^2 \lesssim 0.001 \times E_{\mathrm{Ch,i}}$$

- Mission-design trajectories guide the captured asteroid on a non-collision course with Earth
  - Failure and loss of control would leave a harmless asteroid in orbit around the sun
- Final orbit destinations chosen for its stability
  - L2, stable high lunar orbit, or other sufficiently stable orbit

Robotic-human synergy

ARM would be the first truly robotic precursor since Surveyor

Asteroid observations and composition are important to solar-system studies and to putative solar-system exploitation

- e.g., volatiles, metals
- ARM could enable new commercialization options

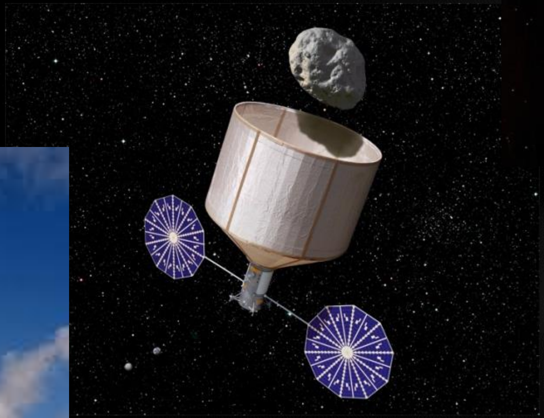
While ARM is not aimed at planetary defense, there are synergies

- Planning for planetary defense benefits from detailed knowledge of potentially hazardous asteroids
  - composition
  - structure
  - capture or deflection technologies

Robotic-human synergy — *Milestones*

ARM launch

Asteroid capture



Emplacement near Moon

Human mission(s)

Scientific study

Commercial options?

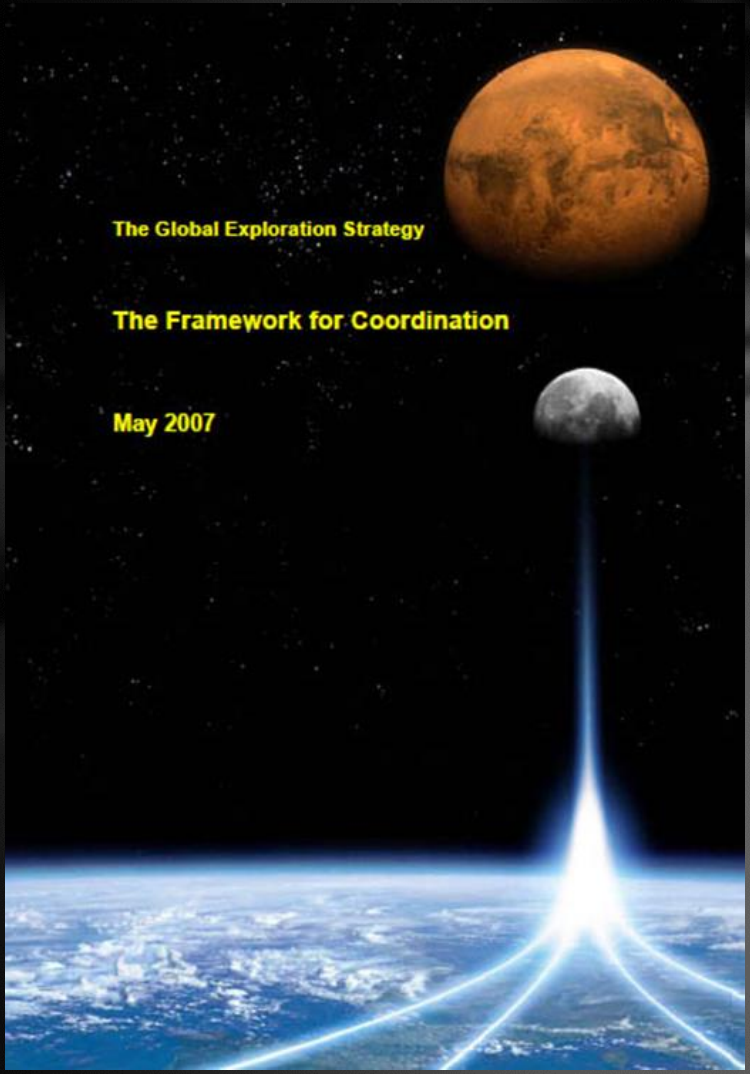
2017 → 2022 → 2025 → 2026 →

International cooperation — I

Eventual human mission may well be international

ARM could be a/the first step in *The Global Exploration Strategy* (May 2007)

Robotic mission admits and invites many affordable cooperative possibilities



Title page: http://esamultimedia.esa.int/docs/GES_Framework_final.pdf

International cooperation — *II*

Robotic sample return is an international pursuit

- Stardust, OSIRIS-REx (NASA)
- Hayabusa 1 and 2 (JAXA)
- Marco Polo (ESA)

Solar Electric Propulsion is an international thrust

Options for international roles include:

- Companion observing spacecraft, e.g., IKAROS free-flying camera
- Payload participation, e.g., High Energy Neutron Detector
- Major subsystem, e.g., capture device

The NEO observing effort is also international

ARM — *Summary and conclusions*

Creates a compelling, exciting, reachable target *beyond the Moon* for next step in exploration

May provide the only possibility for humans to reach an asteroid by the mid-2020s

Creates a meaningful human science, technology, and operations experience, with a significant public-appeal potential

Advances robotic SEP to enable this mission concept

Requires uncertainty reduction for ARM success

Has technology tangencies with planetary defense

Represents a new synergy between robotic and human missions for exploration, science, technology, and applications development

Offers a platform and an opportunity that would host and extend international cooperation

Thank you

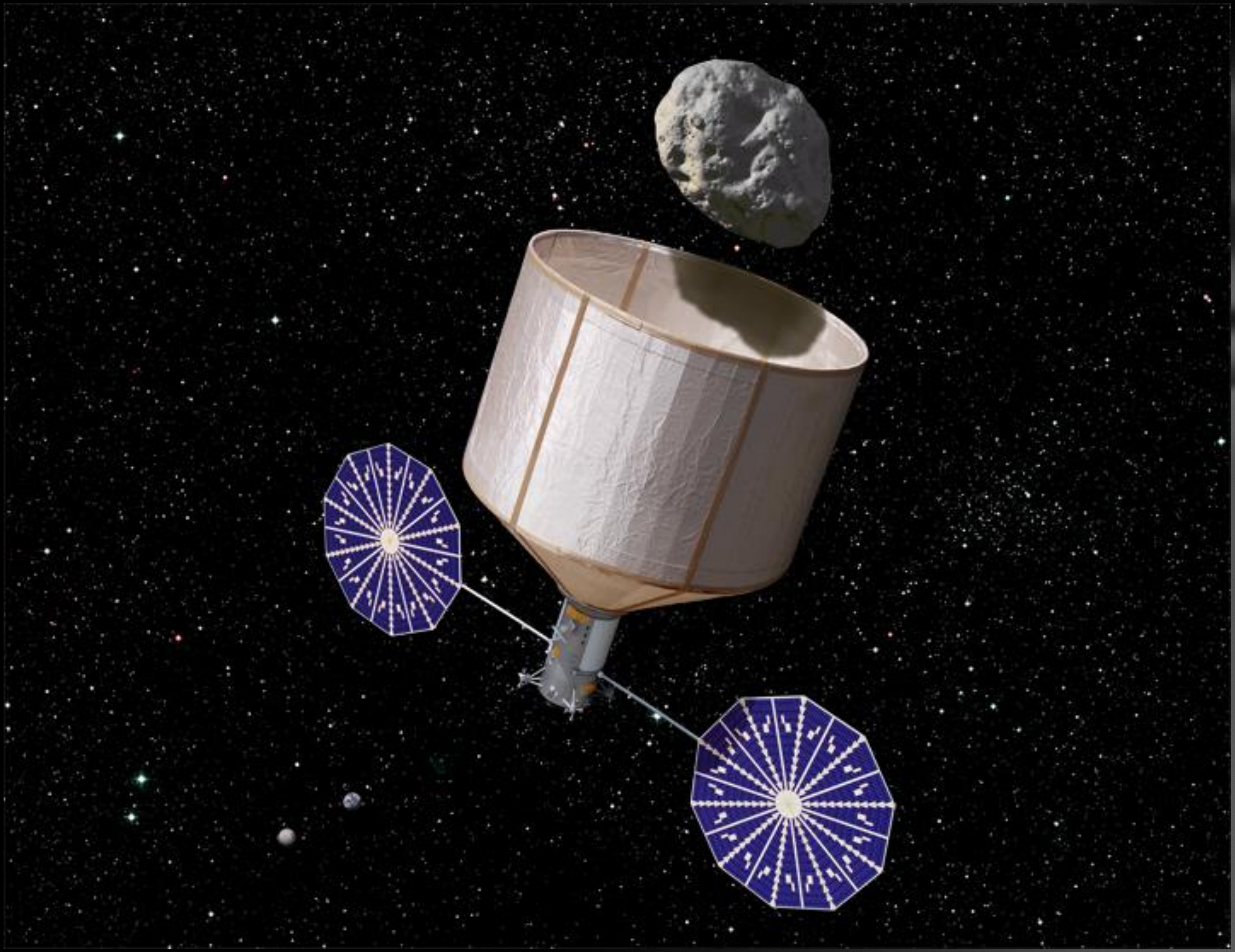


Image credit: Rick Sternbach / Keck Institute for Space Studies

Back-up material

KISS ARM workshop (Phase-1) participants

Carl Allen, NASA/JSC

David Baughman, Naval Postgraduate School

Julie Bellerose, NASA ARC

Bruce Betts, The Planetary Society

John Brophy (co-lead), NASA/Caltech-JPL

Mike Brown, Caltech

Michael Busch, UCLA

John Casani, NASA/Caltech-JPL

Marcello Coradini, ESA

Fred Culick (co-lead), Caltech

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Paul Dimotakis, Caltech

Martin Elvis, Harvard-Smithsonian Center for Astrophysics

Louis Friedman (co-lead), The Planetary Society

Ian Garrick-Bethell, UCSC

Robert Gershman, NASA/Caltech-JPL

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Damon Landau, NASA/Caltech-JPL

Chris Lewicki, ArkydAstronautics

John Lewis, U. 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/Caltech-JPL

Nathan Strange, NASA/Caltech-JPL

Marco Tantardini, The Planetary Society

Brian Wilcox, NASA/Caltech-JPL

Colin Williams, NASA/Caltech-JPL

Willie Williams, NASA/Caltech-JSC

Don Yeomans, NASA/Caltech-JPL

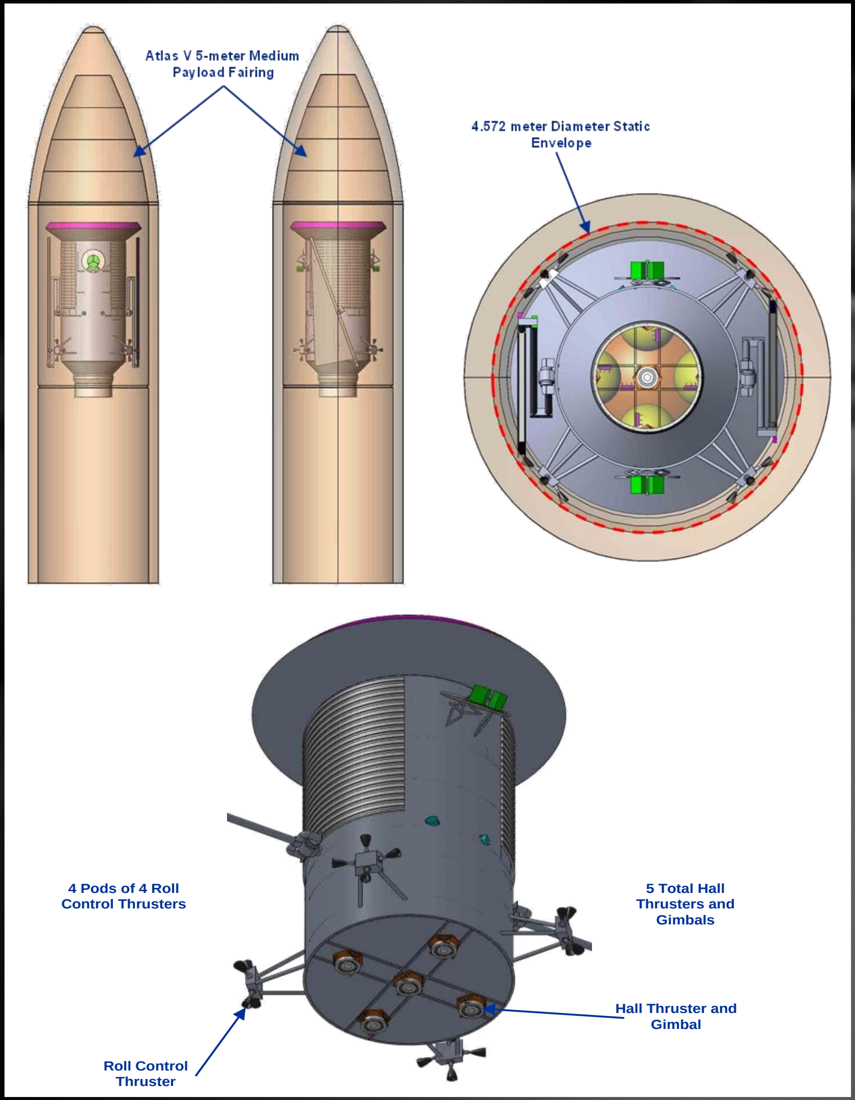
Conceptual ACR spacecraft — *III*

Top:

- Stowed configuration

Bottom:

- Bottom view of the conceptual ACR spacecraft showing the five 10-kW Hall thrusters and the RCS thruster clusters.



Conceptual flight-system design by the NASA/GRC COMPASS team, with guidance by the KISS team (Brophy *et al*. 2012 Asteroid Retrieval Feasibility. KISS final report).

Solar Electric Propulsion — *II*

Current vision is for EP system components to be qualified at the component level (as was done for the Dawn mission):

- Hall thrusters
- Power-processing units (PPUs)
- Thruster gimbals
- Solar arrays
- Solar-array drive assemblies
- ++

Flight system design is dominated by

- The size of the xenon tanks ($m_{\mathrm{Xe}} \leq 13$ tons)
- Solar-array accommodation in stowed configuration
- Thermal-system design to reject ~ 3 kW PPU waste heat

Trajectory parameters for 2008HU4 mission

Parameter	Value	Comments
SEP power (EOL)	40 kW	
Specific impulse, I_{sp}	3000 s	
EP system efficiency	60%	
Spacecraft dry mass	5.5 t	
Launch: Atlas V 551-class		
Launch mass to LEO	18.8 t	
Spiral time	2.2 years	LEO to lunar gravity assist
Spiral Xe used	3.8 t	
Spiral ΔV	6.6 km/s	
Mass at Earth escape	15.0 t	
Transfer to the NEA		
Earth escape C3	2 km^2/s^2	Lunar gravity assist
Heliocentric ΔV	2.8 km/s	
Flight time	1.7 years	
Xe used	1.4 t	
Arrival mass at NEA	13.6 t	
NEA stay time	90 days	
Assumed asteroid mass	≤ 1300 t	
Transfer to Earth-Moon System		
Departure mass: S/C + NEA	1313.6 t	
Heliocentric ΔV	0.17 km/s	
Flight time	6.0 years	
Xe used	7.7 t	
Mass at lunar-gravity assist	1305.9 t	
Escape/capture C3	2 km^2/s^2	Lunar gravity assist
Total Xe used	12.9 t	
Total flight time	10.2 years	

Data for Slide 15 (From Brophy *et al*. 2012 Asteroid Retrieval Feasibility. KISS final report).