ASTEROID RETURN MISSION (ARM)

2012 workshop report and ongoing study summary

Caltech Keck Institute for Space Studies (KISS)

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Asteroid-return mission (ARM) study — 1

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

**Composition:**
- Carbonaceous (C-type), density/strength of “dried mud”
- A rubble pile would break up

**Spacecraft trajectory/control**

**Stable destination orbit:**
- E-M L$_2$, 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: $d_{\text{Ch},i} \sim 15 - 17 \text{ m}, \ m_{\text{Ch},i} \approx 11,000 \text{ tons}; \ u_{\text{Ch},i} \approx 19 \text{ km/s}$

Apollo program returned \( \sim 400 \) kg of moon rocks, over six missions.

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

This study is evaluating the feasibility of returning an entire \( \sim 7 \text{m} \) NEA, with a mass \( \sim 5 \times 10^5 \) kg \( \pm \), to either L2 or a high lunar orbit, by 2026.
Target asteroids — I

Population of NEAs by Size, Brightness, Impact Energy & Frequency (Harris 2006)

Impact Energy, MT

Assumes average density and 20 km/sec impact velocity

Absolute Magnitude $H$

Diameter, Km

Numbers (powers of 10)

Impact Interval, years

Chelyabinsk

Tunguska

Protected by Earth's Atmosphere

Assumes average albedo of 0.14

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

Prelim. spin rate: $\lesssim 10 \text{ rph}$

Imparted $\Delta V \leq 0.2 \text{ km/s}$
- Max $\Delta V \sim 2.6 \text{ km/s}$ with lunar-g assist
- Depends on target-asteroid mass

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

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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 serendipituous

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

* $V_\infty$ 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)
Observational campaign — *What’s needed*

Increase NEO discovery rate to $\sim 10$/day

Yield: $\sim 5$ 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

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<th>Time since discovery</th>
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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).
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).
## Master Equipment List (MEL)

Launch vehicle capability to LEO: 18,000 kg

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<tr>
<th>WBS Number</th>
<th>Description</th>
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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).
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**: $m_{\text{Xe}} \leq 13$ tons at launch
- **Specific impulse**: $I_{\text{sp}} \sim 3000$ 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**: $m_{\text{Xe}} \sim 0.425$ tons at launch
- **SEP cost**: $1M/kW for the solar arrays

SEP is assessed to be an enabling technology for ARM
Heliocentric frame

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

Initial launch mass:

\[ m_i \sim 18 \text{ tons} \]

Return mass: \( m_r \sim 1300 \text{ tons} \)

Mass amplification: \( \frac{m_r}{m_i} > 70:1 \)

Total flight time: \( \tau_f \sim 10 \text{ years} \)

- 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.
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
  \[0.98 \times 1.5 \text{ AU}\]
- 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.
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

1. Launch
   - Earth
   - Atlas V 551

2. Separation & S/A Deployment
   - Moon’s Orbit
   - Spiral Out to Moon (2.2 years)

3. Spiral Out to Moon (2.2 years)
   - LEO Circular Orbit
   - 407 km

4. Lunar Gravity Assist
   - Moon’s Orbit

5. Cruise to Asteroid (1.7 years)
   - Asteroid Orbit

6. Asteroid Operations (90 days: Deploy bag, capture and de-tumble asteroid)
   - Asteroid Orbit

7. Return to Lunar Orbit (2 to 6 years)
   - Lunar Orbit

8. Lunar Gravity Assist
   - Lunar Orbit
   - 407 km LEO Circular Orbit

9. Transfer to high Lunar orbit
   - Lunar Orbit

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.
Multiple and independent safety layers and factors

• A 7 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:
    \[ E_e = \frac{1}{2} m_e U_e^2 \leq 0.001 \times E_{Ch,i} \]

• 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
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
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
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
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**
John Dankanich, NASA/GRC
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
Tom Jones, Florida Institute for Human and Machine Cognition

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
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).
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 ($m_{\text{Xe}} \leq 13$ tons)
- Solar-array accommodation in stowed configuration
- Thermal-system design to reject $\sim 3$ kW PPU waste heat
### Trajectory parameters for 2008HU₄ mission

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEP power (EOL)</td>
<td>40 kW</td>
<td></td>
</tr>
<tr>
<td>Specific impulse, $I_{sp}$</td>
<td>3000 s</td>
<td></td>
</tr>
<tr>
<td>EP system efficiency</td>
<td>60%</td>
<td></td>
</tr>
<tr>
<td>Spacecraft dry mass</td>
<td>5.5 t</td>
<td></td>
</tr>
<tr>
<td>Launch: Atlas V 551-class</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Launch mass to LEO</td>
<td>18.8 t</td>
<td></td>
</tr>
<tr>
<td>Spiral time</td>
<td>2.2 years</td>
<td></td>
</tr>
<tr>
<td>Spiral Xe used</td>
<td>3.8 t</td>
<td></td>
</tr>
<tr>
<td>Spiral ΔV</td>
<td>6.6 km/s</td>
<td></td>
</tr>
<tr>
<td>Mass at Earth escape</td>
<td>15.0 t</td>
<td></td>
</tr>
<tr>
<td>Transfer to the NEA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Earth escape C₃</td>
<td>2 km²/s²</td>
<td>Lunar gravity assist</td>
</tr>
<tr>
<td>Heliocentric ΔV</td>
<td>2.8 km/s</td>
<td></td>
</tr>
<tr>
<td>Flight time</td>
<td>1.7 years</td>
<td></td>
</tr>
<tr>
<td>Xe used</td>
<td>1.4 t</td>
<td></td>
</tr>
<tr>
<td>Arrival mass at NEA</td>
<td>13.6 t</td>
<td></td>
</tr>
<tr>
<td>NEA stay time</td>
<td>90 days</td>
<td></td>
</tr>
<tr>
<td>Assumed asteroid mass</td>
<td>≤ 1300 t</td>
<td></td>
</tr>
<tr>
<td>Transfer to Earth-Moon System</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Departure mass: S/C + NEA</td>
<td>1313.6 t</td>
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</tr>
<tr>
<td>Heliocentric ΔV</td>
<td>0.17 km/s</td>
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<tr>
<td>Flight time</td>
<td>6.0 years</td>
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</tr>
<tr>
<td>Xe used</td>
<td>7.7 t</td>
<td></td>
</tr>
<tr>
<td>Mass at lunar-gravity assist</td>
<td>1305.9 t</td>
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</tr>
<tr>
<td>Escape/capture C₃</td>
<td>2 km²/s²</td>
<td>Lunar gravity assist</td>
</tr>
<tr>
<td>Total Xe used</td>
<td>12.9 t</td>
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</tr>
<tr>
<td>Total flight time</td>
<td>10.2 years</td>
<td></td>
</tr>
</tbody>
</table>

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