Asteroid Mining Project

Astrotecture™
Marc M. Cohen, Architect P.C.
a California professional service corporation
4260 Terman Drive #104
Palo Alto, CA 94306
http://www.astrotecture.com

Presentation to the
International Symposium on
Asteroid Mitigation and Exploration
5 April 2011
Texas A & M University

Asteroid Mining Project Team

- **PI for Spacecraft: Marc M. Cohen, Arch.D**
  - Space Architect, Human Systems Engineer
  - 26 Years at NASA-Ames Research Center
  - 4.5 Years at Northrop Grumman Aerospace Systems
- **CoI for Trajectories: Warren W. James**
  - Consulting Orbital Mechanic
  - 40 years in Aerospace Industry
- **CoI for Mining and Robotics: Kris Zacny, PhD**
  - Mining and Robotics Engineer
  - Honeybee Robotics (10 Years)

Asteroid Mining Project: OBJECTIVES

- The project is a new team effort to develop advanced concepts and analyses to enable:
  - Deep Space-Based Industry
  - A Space-Based Economy that yields a profit
  - The establishment of the basis to become truly a space-faring species.

FIGURE 1. Cover of ANALOG, (July 1961) showing an iron mining and steel-smelting operation at an unspecified asteroid. Art Credit: Gene Thomas.

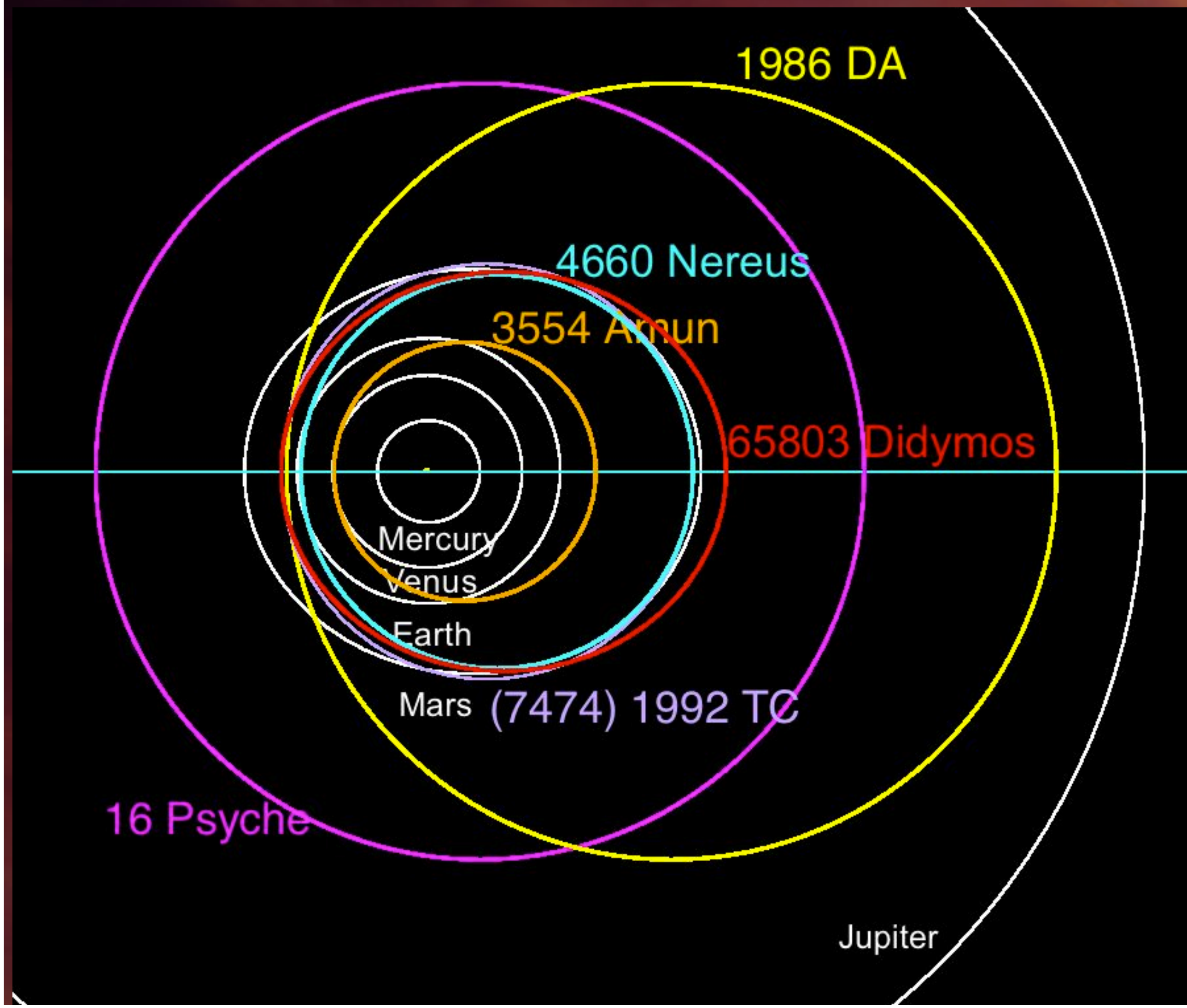
“Mining the Sky”

- Lewis, John (1995). Mining the Sky: Untold Riches from the Asteroids, Comets, and Planets, Helix Books.
- Lewis estimated the value of Iron/Nickel and Platinum group metals in 3554 Amun at $20,000,000,000,000.
- However, 3554 Amun albedo may be misleading – density is too low.
- 1986 DA may offer an alternative at ~ $20,000,000,000

FIGURE 2. Artist’s rendering of an EVA Astronaut during an asteroid mining Mission.

Similarities of Mars and Asteroid Missions for Metallic M-Types

Major Axes Aligned Coplanar, Perihelia to Left



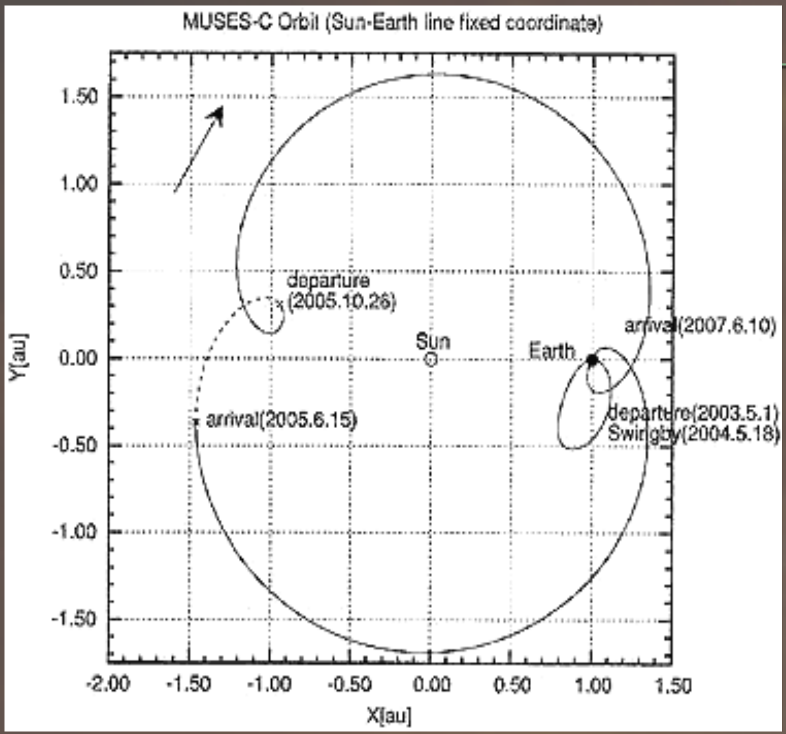
- 16 Psyche: Largest M-type in the Main Belt.
- 1986 DA is an Amor, Mars-Crosser and Main Belt.
- 1992 TC is Mars-crossing Amor.
- 3554 Amun is an Earth-crossing Aten.
- 4660 Nereus is a Earth- and Mars-crossing Aten
- 65803 Didyos is a Mars-Crossing Amor

Assumptions of this Project

- 1. Deploy a multispectral asteroid observatory to Venus orbit.
- 2. Revision of the Outer Space Treaty to allow private property on Asteroids
- 3. Assemble an in-space fueling depot at one of the aligned Lagrange points.
- 4. Form an international program to send robotic spacecraft systematically to explore the NEA population.

Japan's Hayabusa Mission to Itokawa: Complex Trajectory Design from LEO

HAYABUSA MISSION



Original trajectory design for the Hayabusa mission. Credit ISAS.

- http://www.isas.ac.jp/e/special/2003/kawaguchi/02.shtml, retrieved 4 SEPT 2009.

ITOKAWA ASTEROID

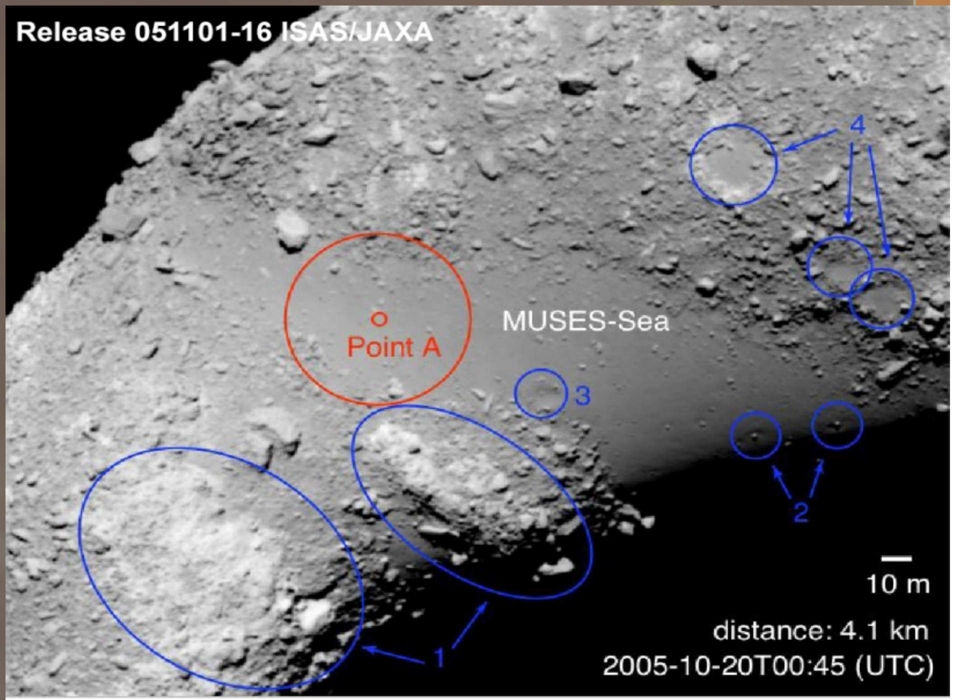


Fig. 11 MUSES-SEA Area, Site candidate-A. Mountains, Boulders and Dimples, Craters.

- FIGURE 3. Hayabusa (2009, Sept). Image of the MUSES-C on asteroid Itokawa. Credit ISAS/ JAXA. Courtesy of the Planetary Society.

Asteroid Mining Project Overview

- **To advance a successful business case for Asteroid Mining, it is necessary to make five arguments:**
  - 1. Abundant and Accessible Minerals
  - 2. Market Demand
  - 3. Transformational Trajectories
  - 4. Robotic Extraction and Processing
  - 5. Human and Robotic Spacecraft

Argument 1: Minerology

Our knowledge of asteroid composition comes primarily from analysis of meteorites, which we believe are mainly collision fragments of asteroids.

We apply this knowledge to asteroids by observing the albedo and spectral results, which for M-Type Asteroids means metallic composition.

Not all M-Types are true metallics; some have similar albedo and spectral type (.9μ emission line) but density is too low.

True metal M-Types constitute about 4% of the known asteroid population.

Metallic M-Type Meteorites

Iron/Nickel Meteorites sometimes contain trace amounts of Platinum group metals and rare earth elements.

Campo iron meteorite

Gibeon iron meteorite slice.

Metallic S-Type Meteorites

Silicaceous or Stony Meteorites sometimes include Iron/nickel

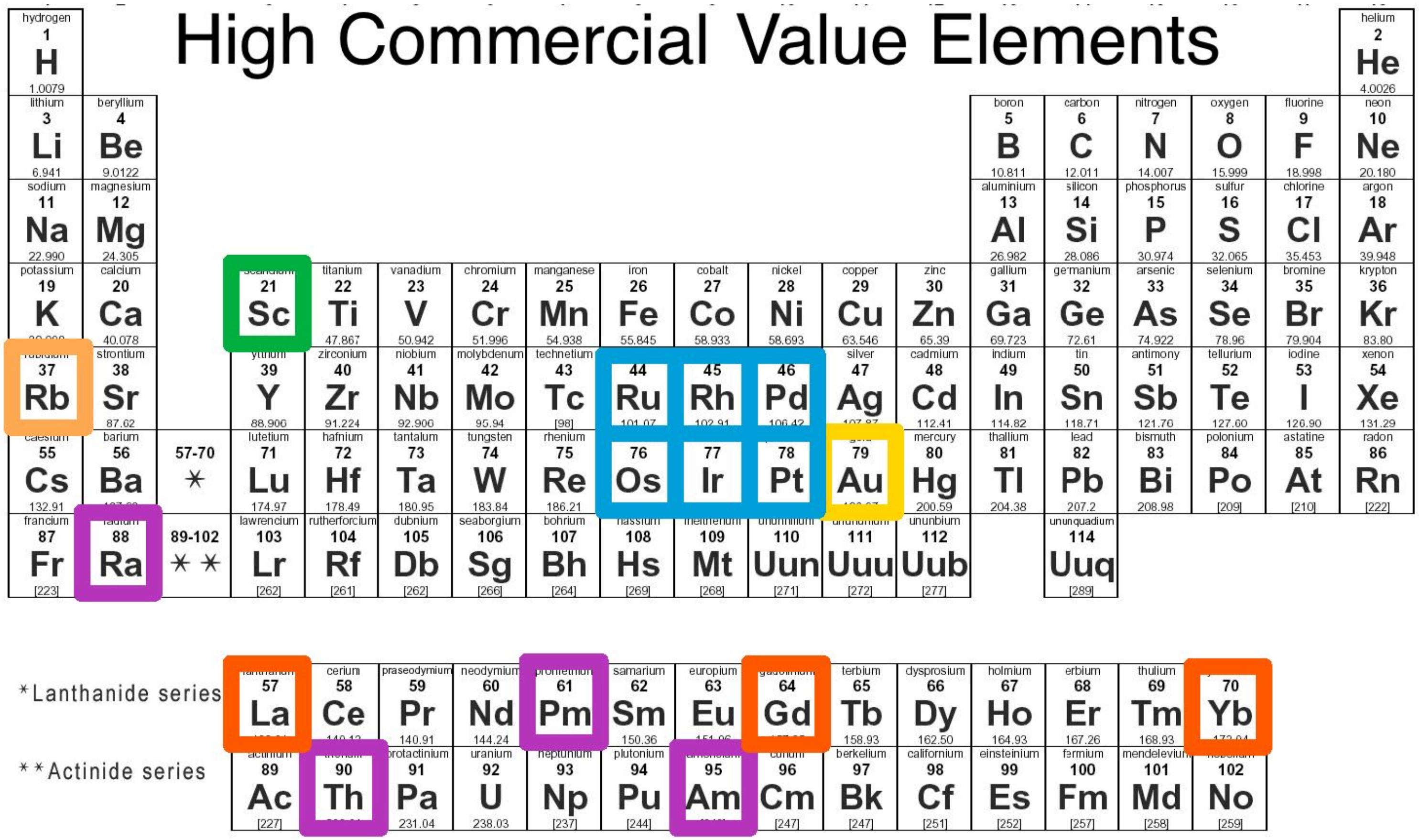
Stony iron meteorite

Silicated iron meteorite

Argument 2: Market Demand

- Currently, among the Transition Metals, the Platinum group, Gold, and Scandium command an increasing price.
- Precious metal demand will continue to increase for the foreseeable future.
- The price of rare earth metals is increasing rapidly because of increasing industrial demand and China's virtual monopoly on production.
- Some of the radioactive elements command very high prices. Some are naturally occurring, produced in reactors, or both.

Commercial High Value Elements On the Periodic Table



Based on Refined & Retail Prices for bars, bullion, ingots, or rods.

High-Value Elements: Alkali and Transition Metals

Z	Symbol	Element	$k/kg	Reference Price Source	Selected Uses	Remarks
Alkali Metals / Alkali Earth Metals						
37	Rb	Rubidium	35.0	elementsales.com	Atomic clocks & GPS frequency standard, electronics, medical devices, ion engines.	
88	Ra	Radium	110,000.0	ask.com	Laboratory, alpha emitter, treatment of bone cancer metastisis.	Difficult to determine price
Transition Element / Platinum Series						
21	Sc	Scandium	8.9	elementsales.com	Aerospace aluminum alloys, metal halide lights.	Usually found with Rare Earths
44	Ru	Ruthenium	35.0	elementsales.com	Hardened electrical contacts, jet turbine blades.	Platinum Group
45	Rh	Rhodium	77.4	eBullionguide.com	Harden alloys, catalytic converters, industrial catalyst.	Platinum Group
46	Pd	Palladium	23.3	TheBullionDesk.com	Catalytic converters, jewelry, dentistry, watches, medical.	Platinum Group
76	Os	Osmium	31.8	elementsales.com	Transmission Electronic Microscopy, (TEM) surgical implants.	Platinum Group
77	Ir	Iridium	33.6	eBullionguide.com	Electrical, electrochemical, catalyst.	Platinum Group
78	Pt	Platinum	57.4	eBullionguide.com	Catalyst, hydrogen electrode, jewelry, watches.	Platinum Group
79	Au	Gold	45.3	TheBullionDesk.com	Jewelry, currency,	

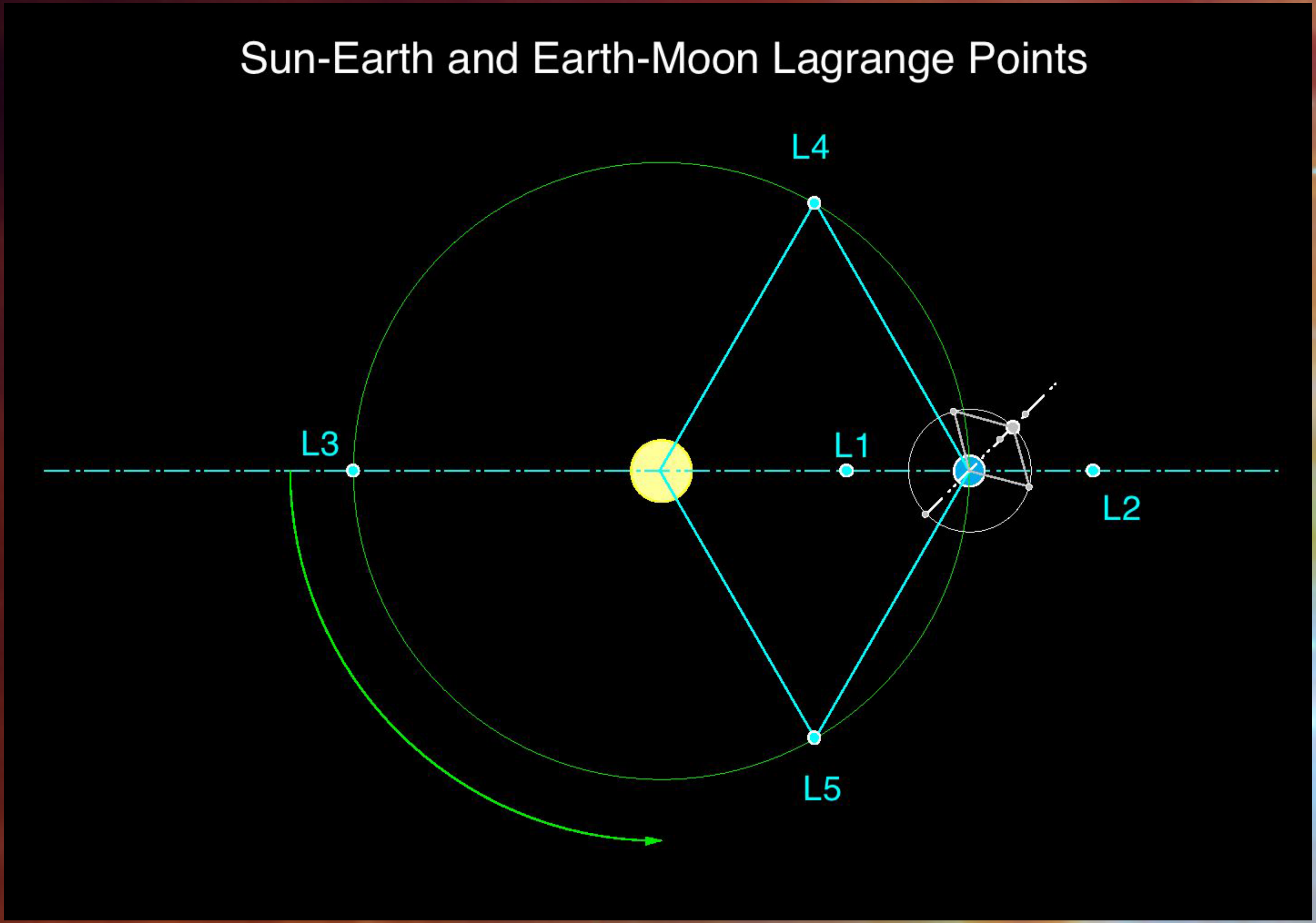
High-Value Elements: Rare Earth Metals

Z	Symbol	Element	$k/kg	Reference Price Source	Selected Uses	Remarks
Rare Earth Series Lanthanides						
61	Pm	Promethium	100.0	chemicool.com	Beta radiation emitter, reliable light source, atomic battery.	China produces 95+% of world supply.
64	Gd	Gadolinium	6.1	elementsales.com	Neutron therapy, MRIs & MRAs, positron emission tomography.	China produces 95+% of world supply.
70	Yb	Ytterbium	14.0	chemicool.com	Optical Media, solid state lasers, fine grain stainless steel.	China produces 95+% of world supply.
71	Lu	Lutetium	6.3	elementsales.com	Magnetic bubble memory, radionucleotide therapy, catalyst for many processes.	China produces 95+% of world supply.
Rare Earth Series Actinides						
90	Th	Thulium	5.6	elementsales.com	Laser, portable X-ray source, high temp superconducter.	Naturally occurring.
95	Am	Americunium	1,500.0	worldnuclear.org	Smoke detectors, ionization detector, radio-thermal generator, nuclear thermal propulsion.	Naturally occurring but also produced in reactors.

Argument 3: Trajectory Design

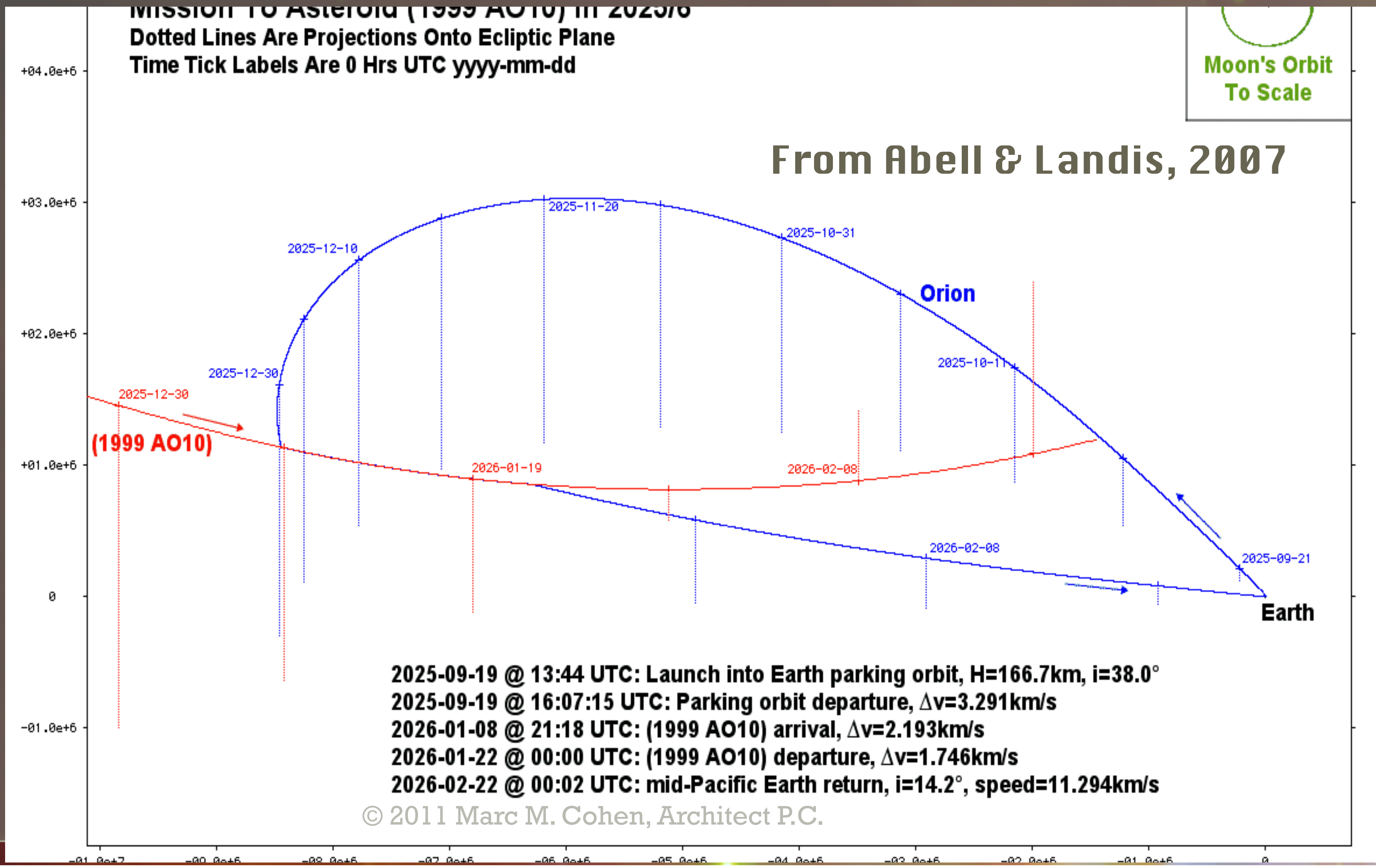
- The key to a transformational solution to trajectory design is to stage from one of the Aligned Lagrange Points.
  - The Lagrange point departure problem makes a rich and complex design trade space.
  - Earth-Moon L1, L2, and L3.
  - Also consider the Sun-Earth L1 and L2.
- Propellant delivered from the Surface of the Earth vs from the Surface of the Moon:
  - Δ from Surface of the Earth to L1 = 13.5 km/s
  - Δ from Surface of the Moon to L1= 2.5 km/s
- We can improve Δv even more by doing Moon or Earth swing-by when departing L1 to an Asteroid.
- The benefits become even greater with return to L1.

Staging from the Colinear Lagrange Points: Design Trade Space

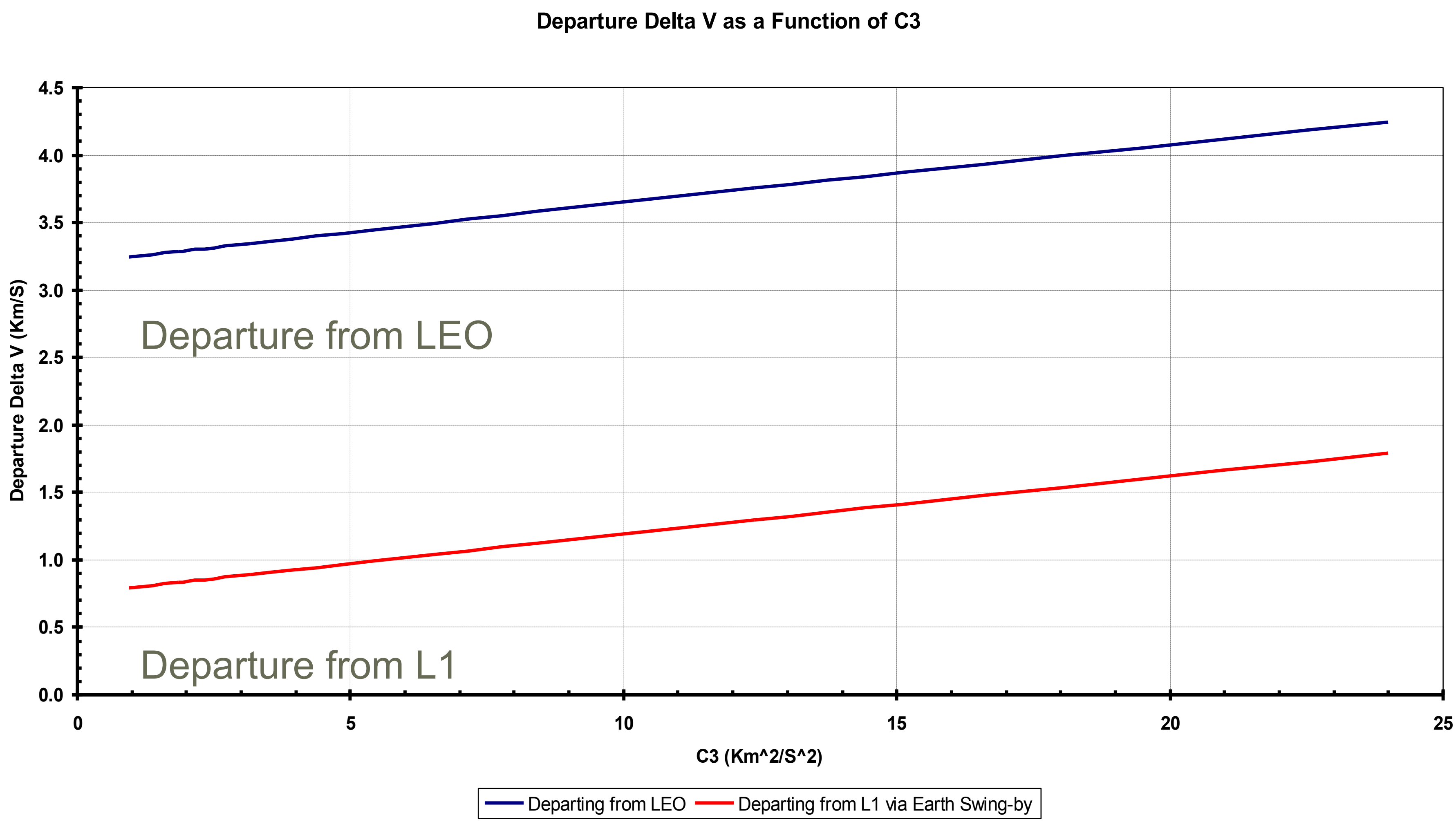


Concept for Human Mission: LEO to 1999 AO10

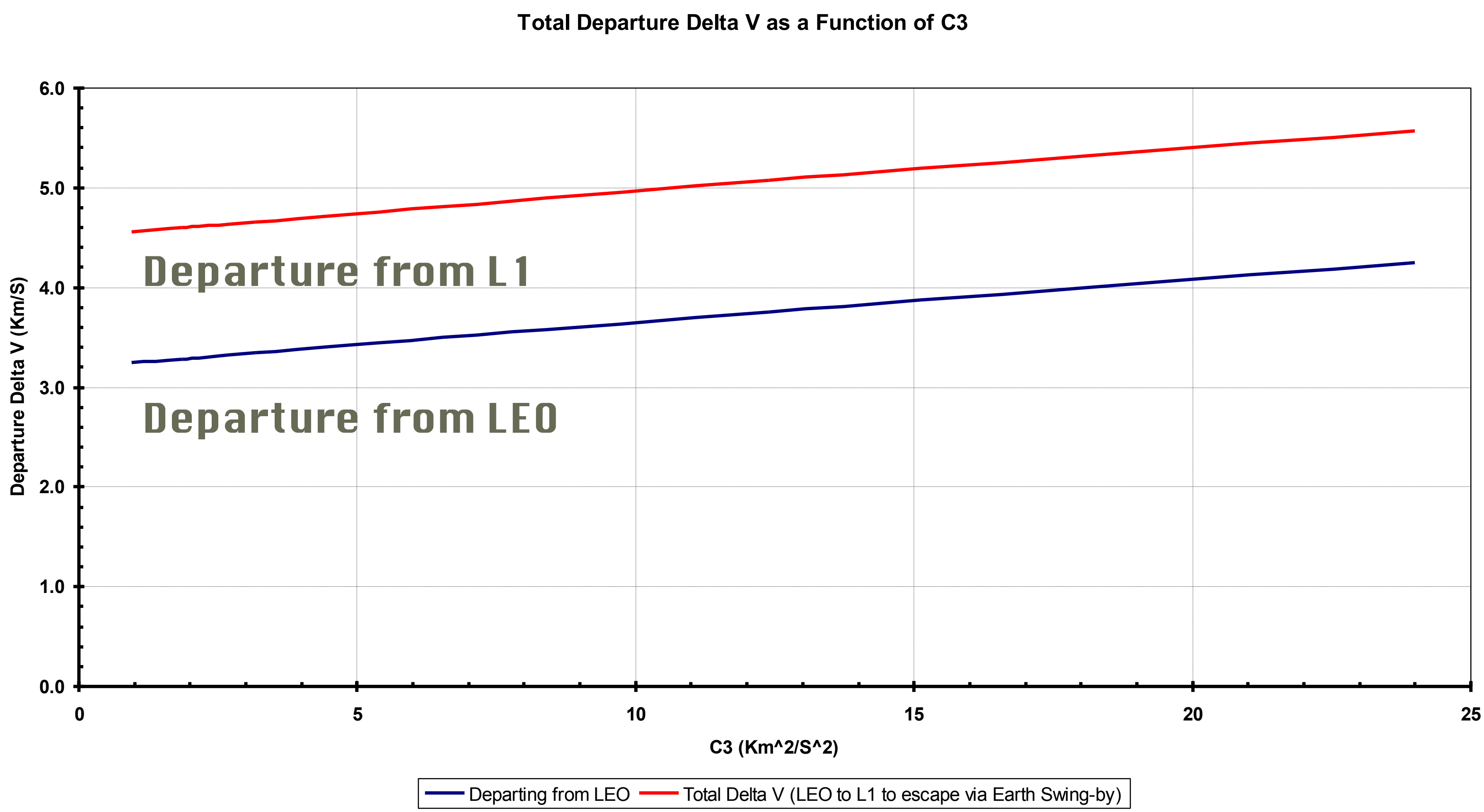
An Apollo Earth-Crosser (but not an M-Type).



Departing from Lunar L1 vs LEO:
Δv required as a function of C3



For the same C3, L1 staging with Earth Swing-by requires higher Δv



Argument 4: Extraction & Processing in Space

- Compared to mining on Earth, an Asteroid poses problems of power and equipment mass for extraction and processing.
- On Earth:
  - Power is plentiful for drilling and processing
  - Explosives may be dangerous but won't send you spinning forever into space
  - Water is plentiful for extraction.
- New technologies for extraction and processing in space must compensate for the lack of these advantages on Earth.
  - Mass reduction and ore concentration is essential for return shipment.
  - Ultimately, refined products go to market; refining in space would have double advantages.

Space Robotic Mineral Extraction, Analysis and Processing

Deployment & Positioning

LIDS Mineral Analyzer

EVA Mechanisms & Tools

Rock Abrasion Tool

HONEYBEE ROBOTICS

Spacecraft Mechanisms Corporation

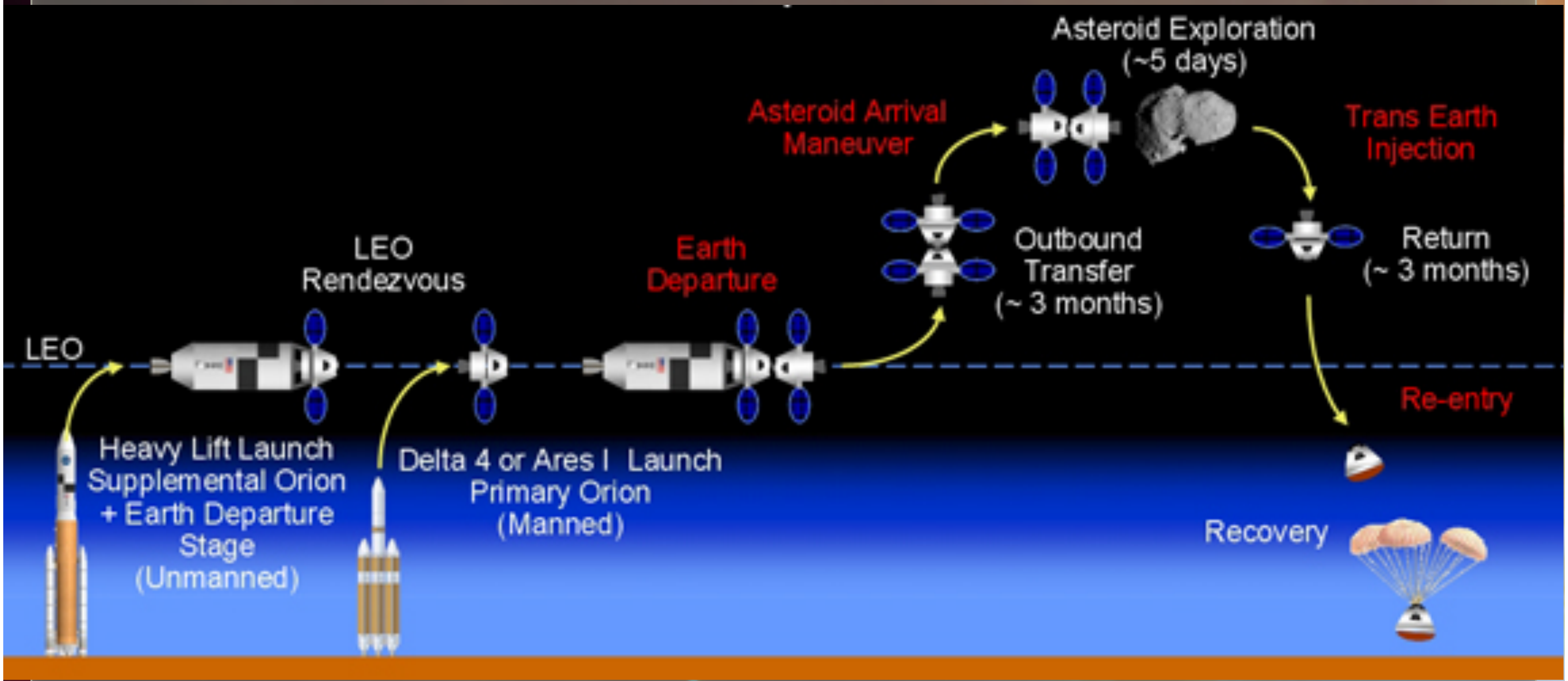
Argument 5: Robotic & Human Spacecraft for Prospecting & Mining

- Robotic Precursors for Prospecting and Surveying are essential.
  - They can use the same L1 Logistics and Trajectories as later human Missions

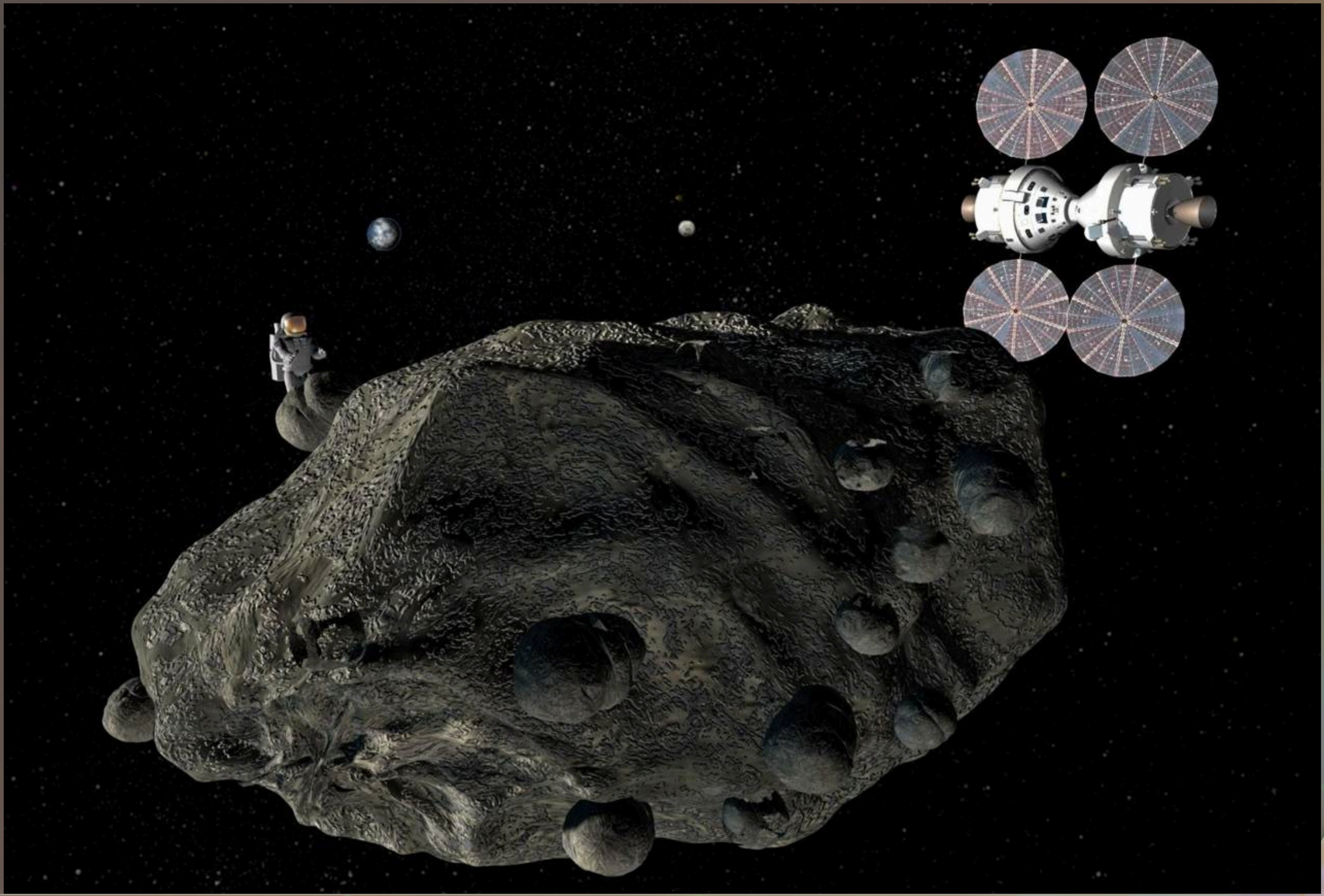
- All Missions will be both Human and Robotic
  - The issue is where in the loop the humans and robots are employed.
  - Robots will always need some human supervision.
  - Humans need robots to do dangerous, repetitious, and boring tasks.

- Early Extraction Missions Require both Humans and Robots
  - There are too many qualitative judgement calls for robots alone.
  - Humans need the practice of mining in space with robots to learn how to innovate and to work efficiently, reliably, and safely.

Conventional Mission Architecture Applied to an Asteroid Exploration (L-M)



Double Orion NEA Mission
(2 Orions without an airlock)



Asteroid Mission with Dedicated "Lander" Module on an Orion

The lander includes an airlock.

All images courtesy of Bruce Damer, President of Digital Space

Initial Concept Integration

- Deploy robotic and uncrewed spacecraft on as slow spiral solar-electric/Ion engine trajectory to Earth-Moon L1.
- Fuel spacecraft with cryogenic propellant from Moon.
- Add lunar water to fill radiation shielding tanks on crew vehicle.
- Crew arrive on a fast trajectory in an Orion-class vehicle, then transfer to the cis-planetary spacecraft.
- Spacecraft departs L1 in correct inclination for asteroid intercept – minimize need for plane changes.
- Rendezvous then “Rock-Dock” at the Asteroid.
- Deploy robots and/or the EVA crew to the surface to begin prospecting and later mining.
- Return to L1.
- Crew transfer to Orion for Earth-return.
- Payload returns to earth via slow inward spiral.

Conclusion

- Our team formed 1 March 2011.
- Each member had worked separately on asteroid missions.
- Now we are learning to work together.
- Abundance of high value metals in Asteroids is still somewhat speculative.
- Market demand seems to be steady for products at competitive prices.
- Trajectory design is the key to making everything possible.
- In-space extraction and processing appears to be the greatest technological challenge.
- Supporting a crew to be healthy and productive in deep space for a year or more is the greatest design challenge.