ECONOMICS OF ASTEROID MINING

SHEN GE
NEHA SATAK
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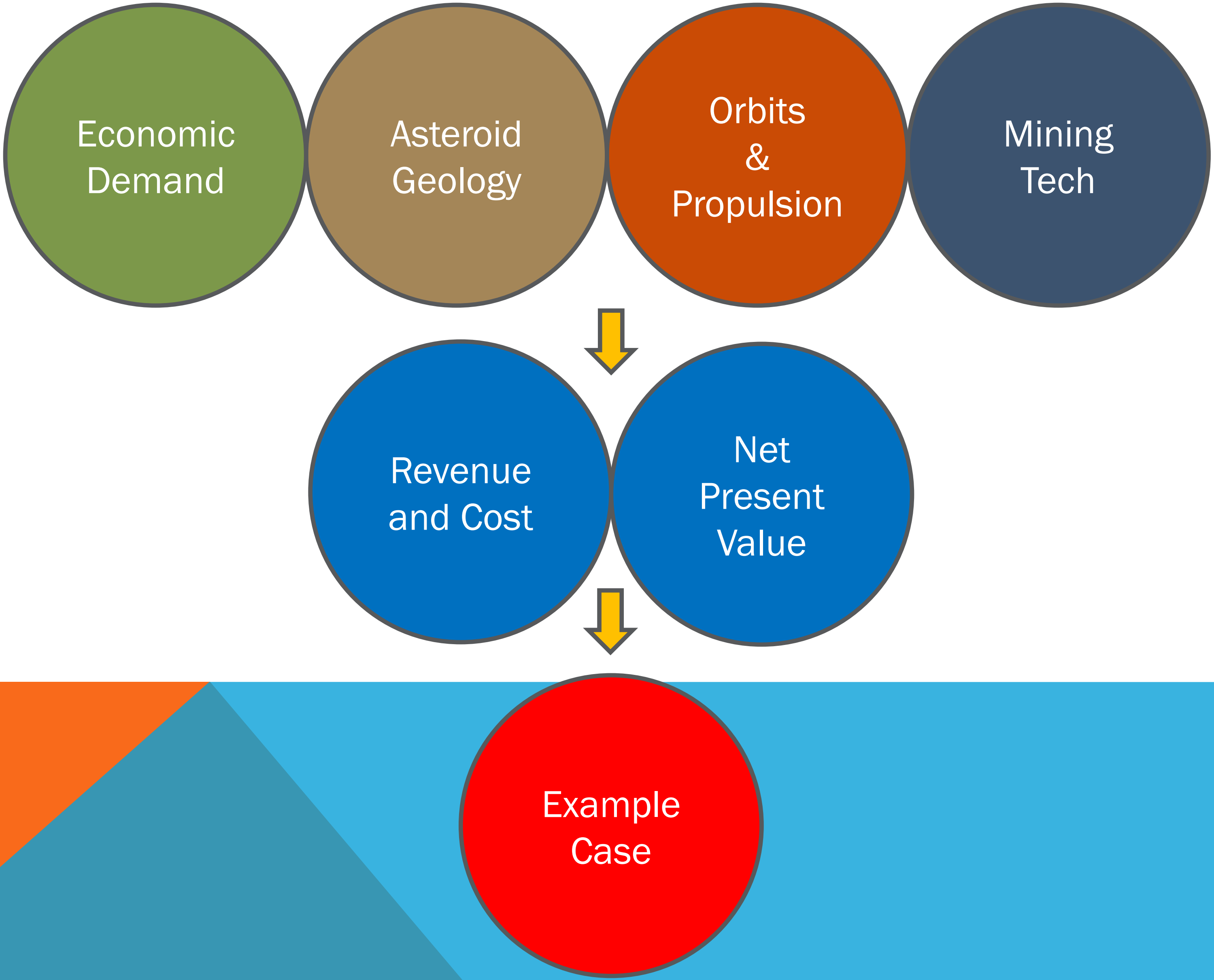
OUTLINE



Economic Demand

Asteroid Geology

Orbits & Propulsion

Mining Tech

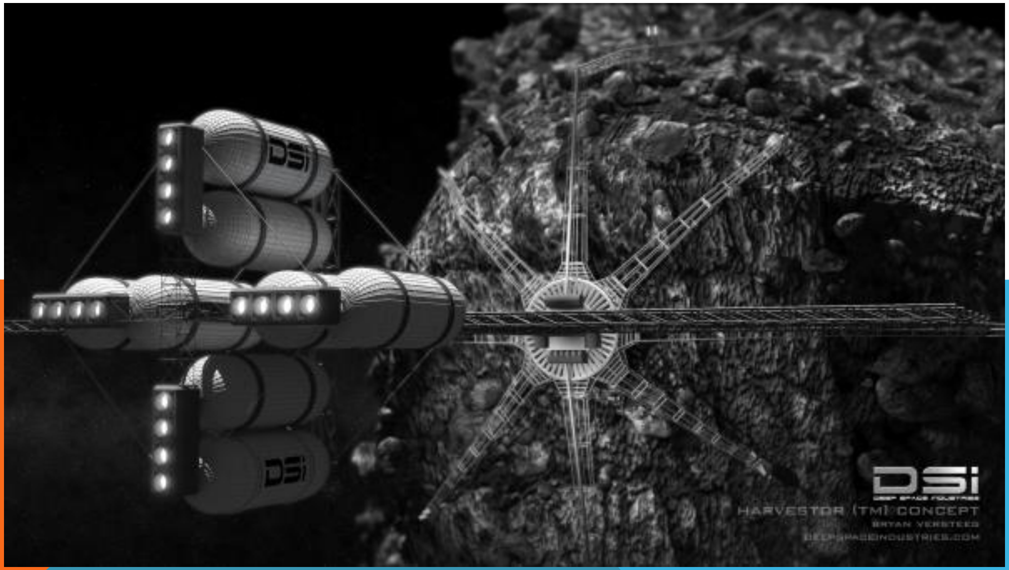
Revenue and Cost

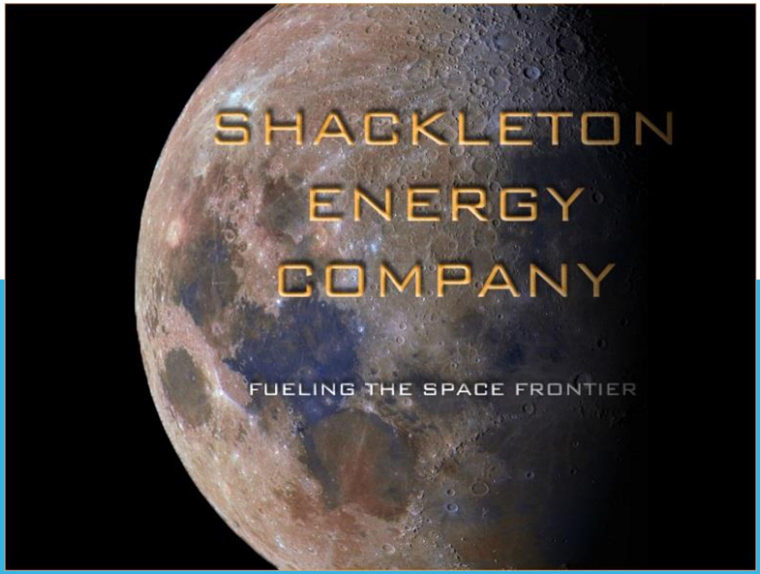
Net Present Value

Example Case

GROWING INTEREST IN SPACE MINING

MARC M. COHEN
ARCHITECT





ASTEROID RESOURCES

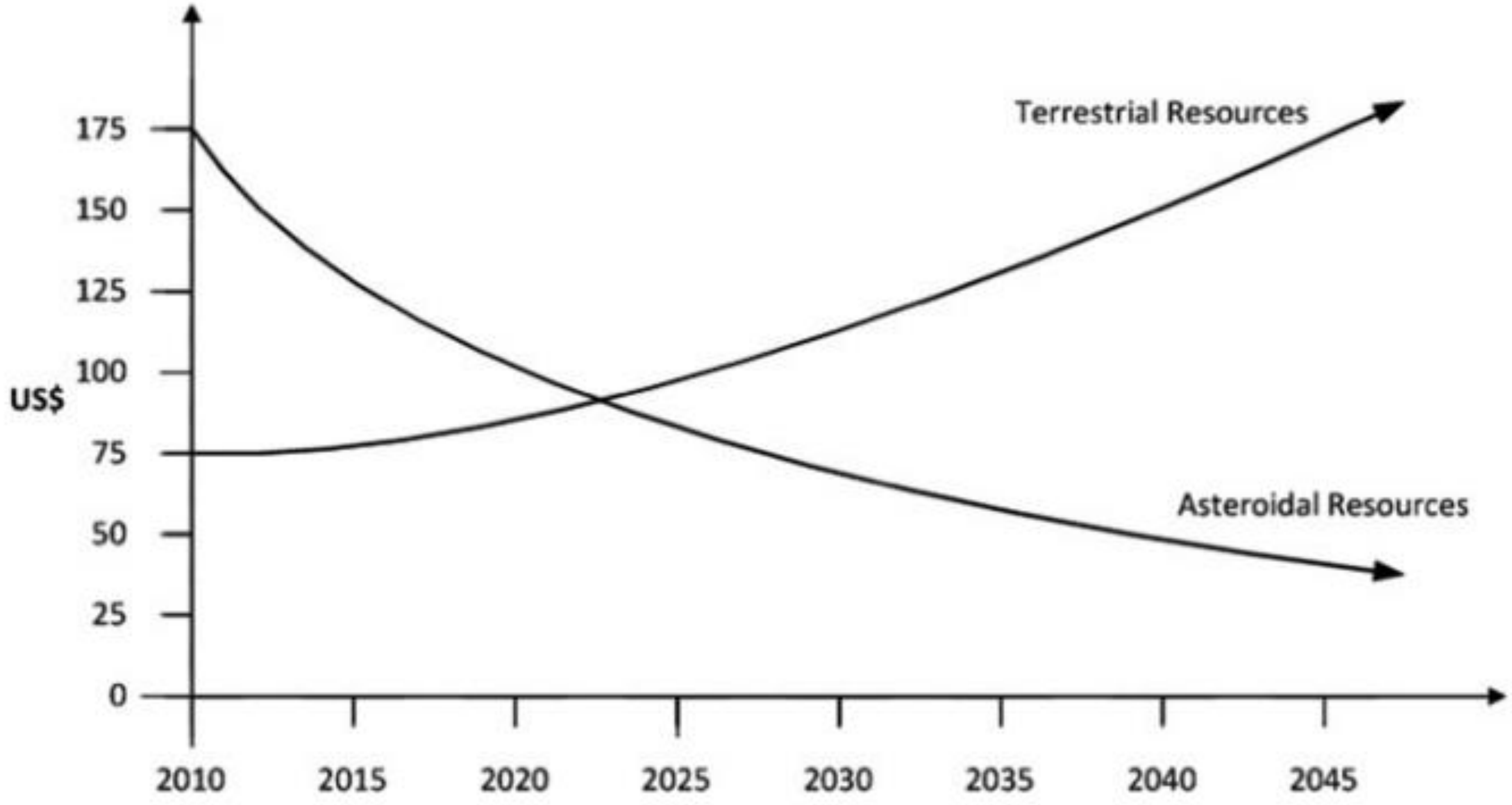


Chart from Charles Gerlach

NEAR-EARTH ASTEROIDS

- Near-Earth Asteroids (NEAs) are of interest due to the relative ease of reaching them.
- All NEAs have perihelion less than 1.3 AUs.

Image Credit: William K Hartmann

ESTIMATED NUMBER OF NEAS

Diameter(m)	>1000	1000-140	140-40	40-1
Distance (km) for which F>100 (λ=0.5 μm)	>20 million	< 20 million, > 400,000	<400,000 (Lunar orbit) >32,000 (GEO orbit)	<32,000 >20
H(absolute magnitude)	17.75	17.75-22.0	22.0-24.75	>24.75
N estimated	966	`14,000	~285,000	??
N observed	899	4,557	2,259	1,685
O/E	93%	~33%	~1%	??

Image Credit: http://www.iau.org/public/nea/

KNOWN NEAS

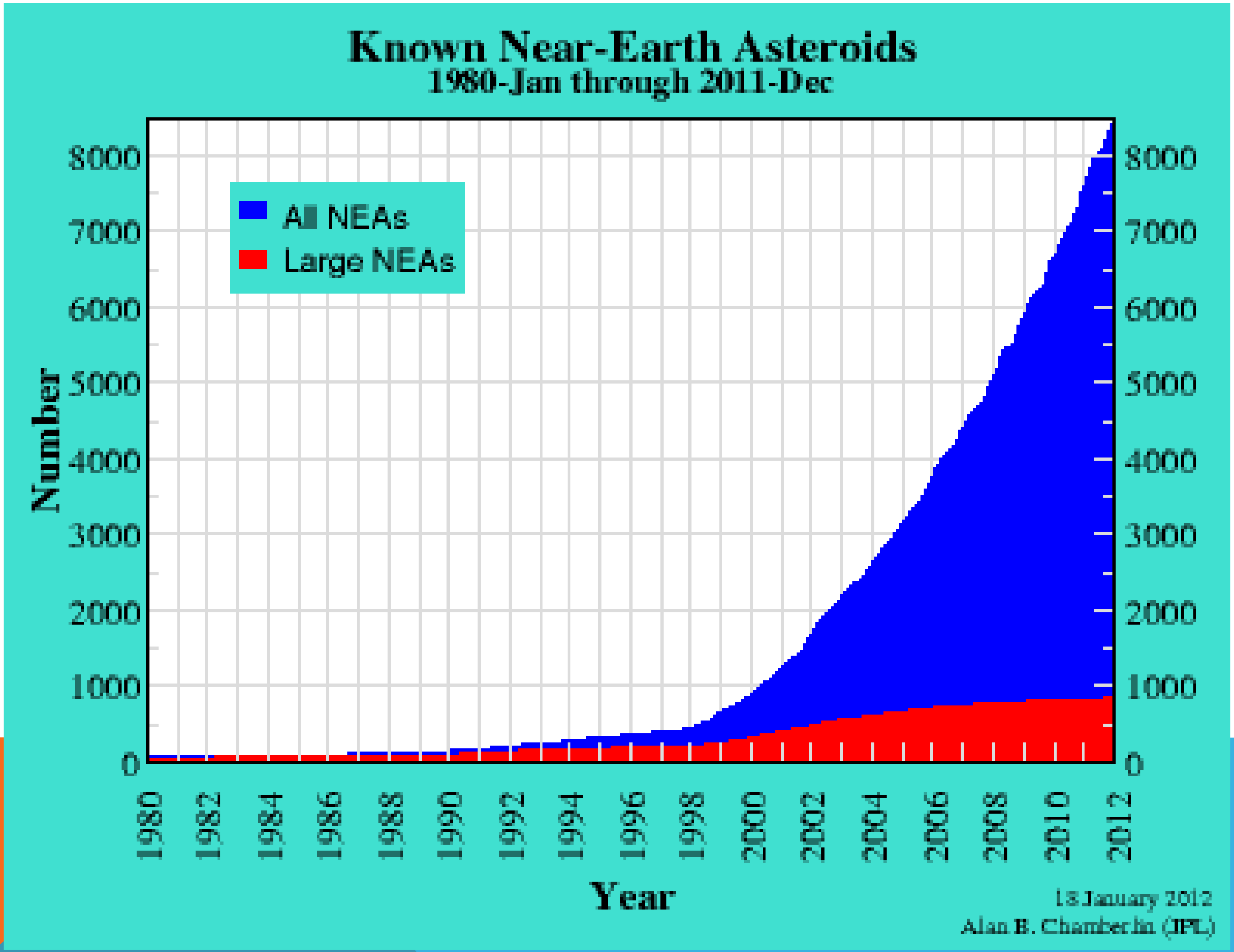
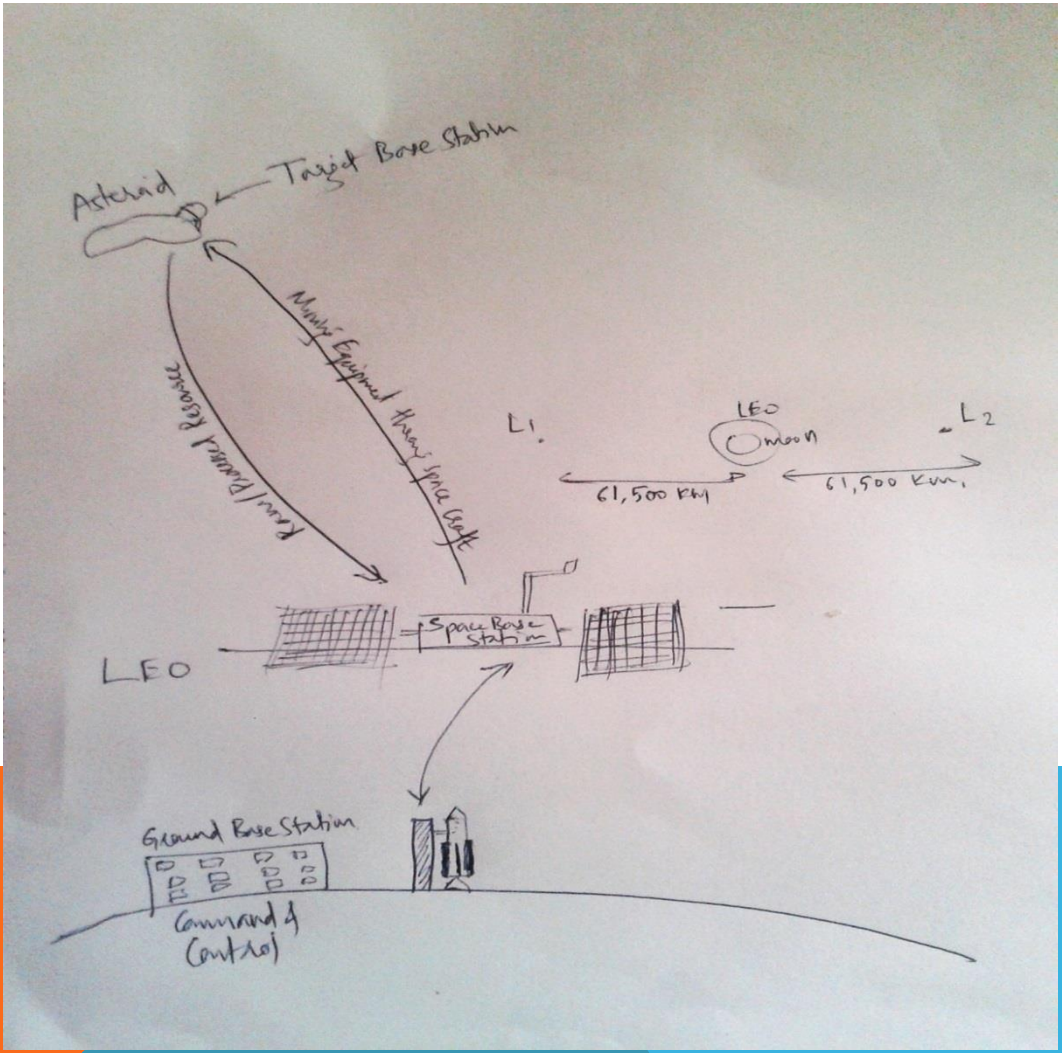


Image Credit: NASA JPL

FROM EARTH TO ASTEROID & BACK



1. Ground Base Station (Earth) to LEO
2. Space Base Station (at LEO)
   - Transportation Hub
   - Communications
   - Fuel Storage
   - Manufacturing
3. Target Base Station (Asteroid)

IMPORTANT QUESTIONS

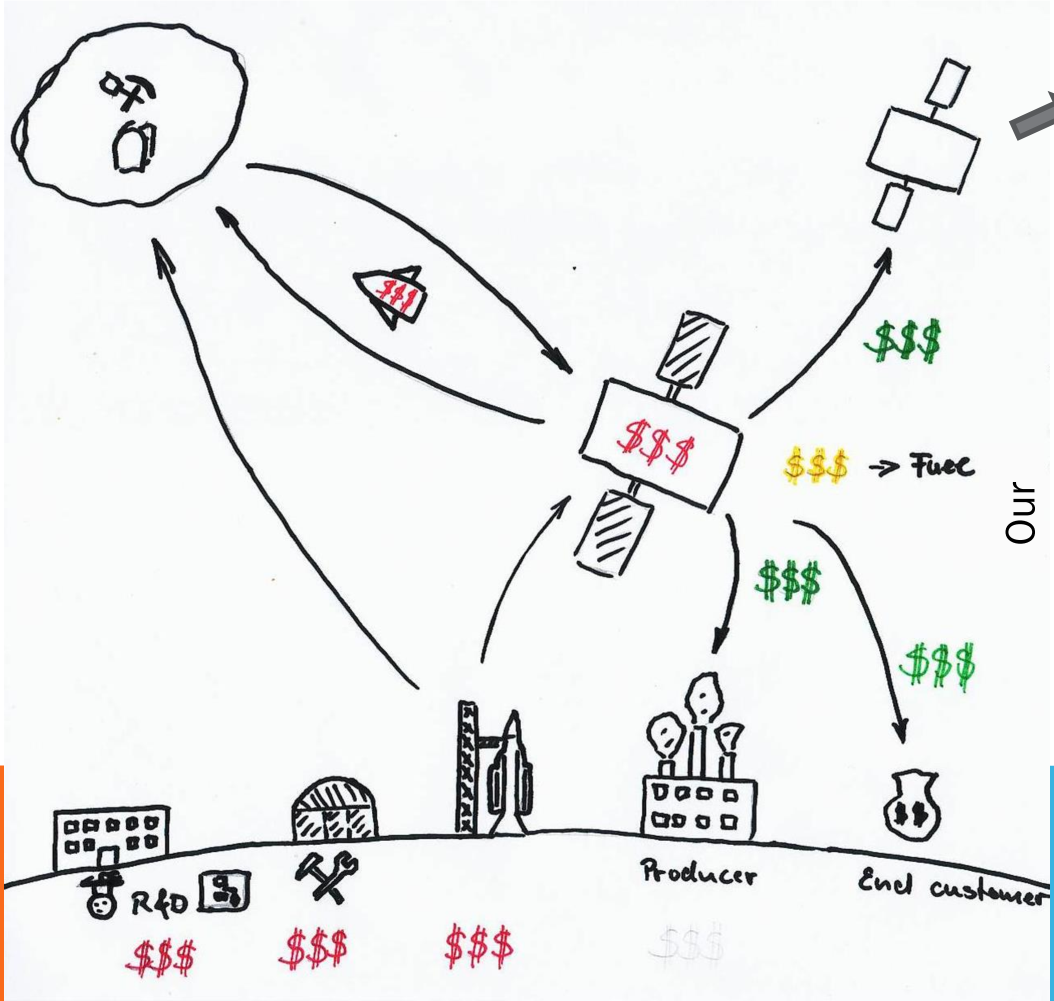
Economic Demand

Asteroid Composition

Astrodynamics and Propulsion

Mining Technologies

ECONOMIC DEMAND



Processor
Producer
End customer
(Space tourist)

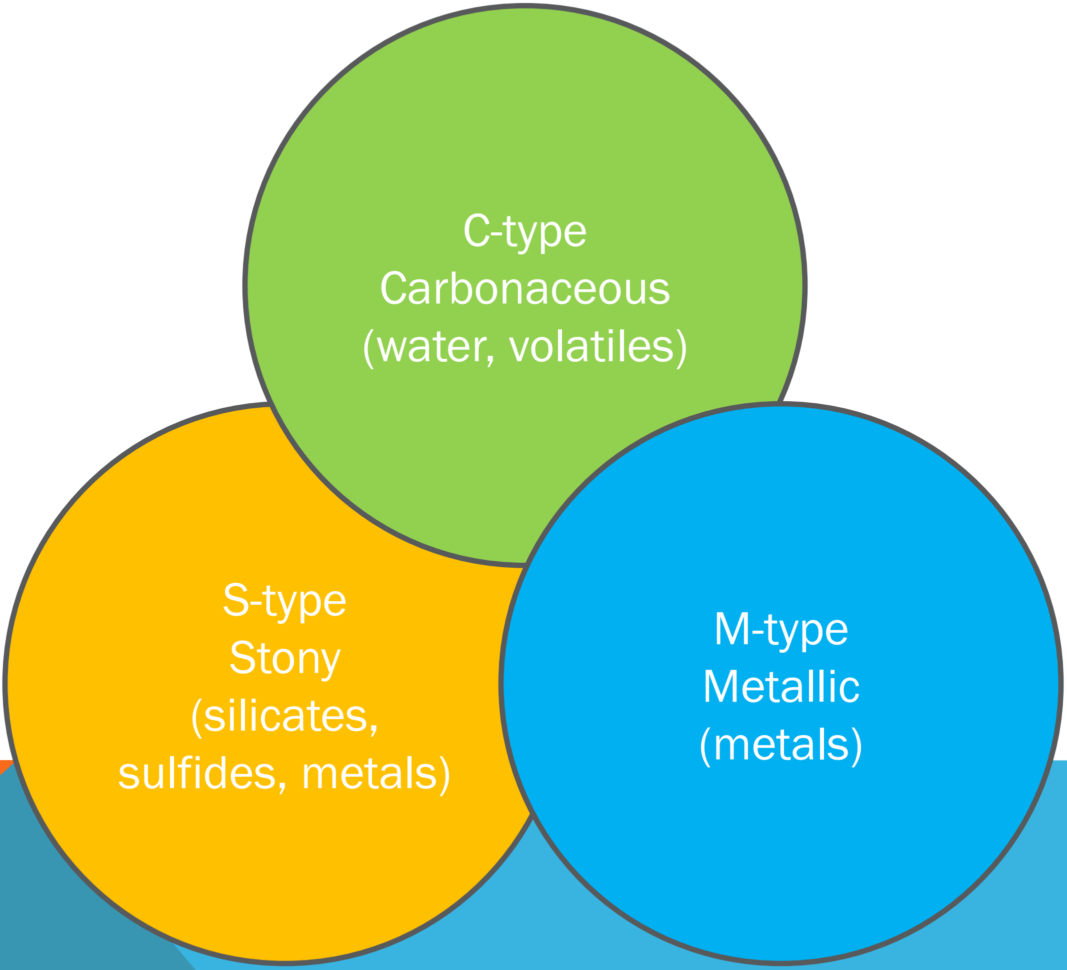
Our Products and services

House tourists
Rent space for science
Reload site / emporium
Rent storage capacity
Space jewelry collection

Processing plant
Storage
Production plant
Fuel station

$$$ costs
$$$ own usage
$$$ revenue

TYPES OF NEAS



C-type
Carbonaceous
(water, volatiles)

S-type
Stony
(silicates,
sulfides, metals)

M-type
Metallic
(metals)

253 Mathilde - 66 × 48 × 44 km
NEAR, 1997

433 Eros - 33 × 13 km
NEAR, 2000

951 Gaspra
18.2 × 10.5 × 8.9 km
Galileo, 1991

5535 Annefrank
6.6 × 5.0 × 3.4 km
Stardust, 2002

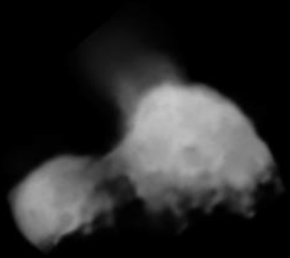
2867 Steins
5.9 × 4.0 km
Rosetta, 2008

25143 Itokawa
0.5 × 0.3 × 0.2 km
Hayabusa, 2005

9969 Braille
2.1 × 1 × 1 km
Deep Space 1, 1999

Dactyl
[(243) Ida I]
1.6 × 1.2 km
Galileo, 1993

243 Ida - 58.8 × 25.4 × 18.6 km
Galileo, 1993



1P/Halley - 16 × 8 × 8 km
Vega 2, 1986

9P/Tempel 1
7.6 × 4.9 km
Deep Impact, 2005

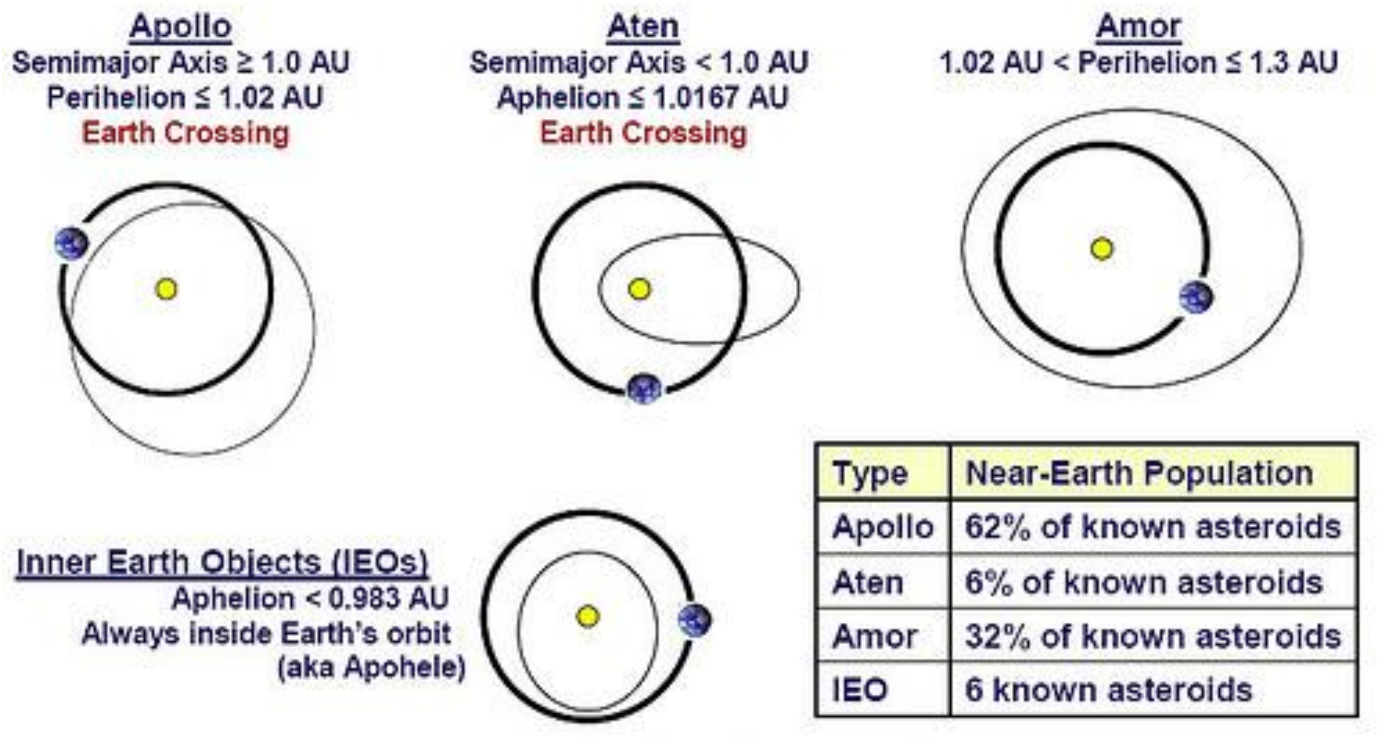
19P/Borrelly
8 × 4 km
Deep Space 1, 2001

81P/Wild 2
5.5 × 4.0 × 3.3 km
Stardust, 2004

MATERIALS FROM NEAS

Material	Product
Raw silicate	Ballast or shielding in space
Water and other volatiles	Propellant in space
Nickel-Iron (Ni-Fe) metal	Space structures Construction on earth
Platinum Group Metals (PGMs)	Catalyst for fuel cells and auto catalyzers on earth Jewelry on earth
Semiconductor metals	Space solar arrays Electronics on earth

NEA ORBIT TYPES



Apollo
Semimajor Axis ≥ 1.0 AU
Perihelion ≤ 1.02 AU
Earth Crossing

Aten
Semimajor Axis < 1.0 AU
Aphelion ≤ 1.0167 AU
Earth Crossing

Amor
1.02 AU < Perihelion ≤ 1.3 AU

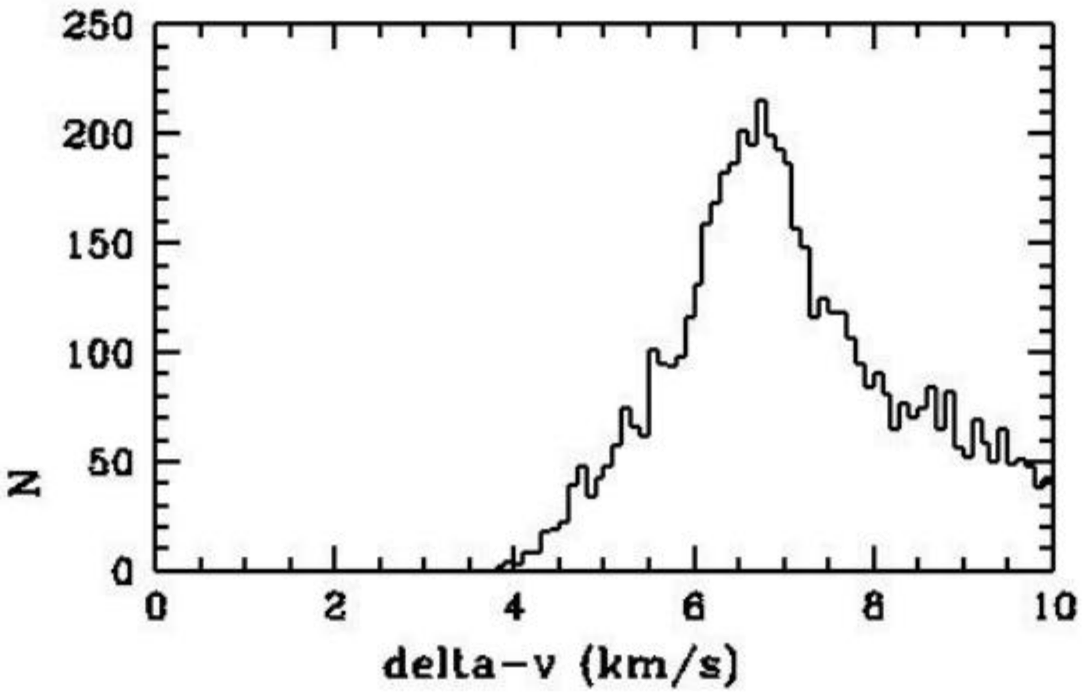
Inner Earth Objects (IEOs)
Aphelion < 0.983 AU
Always inside Earth's orbit
(aka Apohele)

Type	Near-Earth Population
Apollo	62% of known asteroids
Aten	6% of known asteroids
Amor	32% of known asteroids
IEO	6 known asteroids

Image Credit: http://neo.jpl.nasa.gov/neo/groups.html

ACCESSIBILITY

We want to find the asteroids with low delta-vs to reduce propellant needed.



Distribution of specific linear momentum of a Hohmann transfer from low Earth orbit (LEO) to NEAs according to Benner.

Image Credit: Elvis, McDowell, Hoffman, and Binzel. “Ultra-low Delta-v Objects and the Human Exploration of Asteroids.”

ACCESSIBILITY: ROCKET EQ

$$\Delta v = V_e \ln (M_o/(M_o-M_p))$$

where

Δv = velocity change
V_e = exhaust velocity
M_o = total mass
M_p = propellant mass

Two Options:

1. Reduce delta-v required for trajectories to enable low-thrust propulsion methods such as electric, solar thermal, or solar sail propulsion.
2. Use chemical propulsion for high thrust trajectories if needed.

ACCESSIBILITY EXAMPLE

“Apollo-Type” Mission

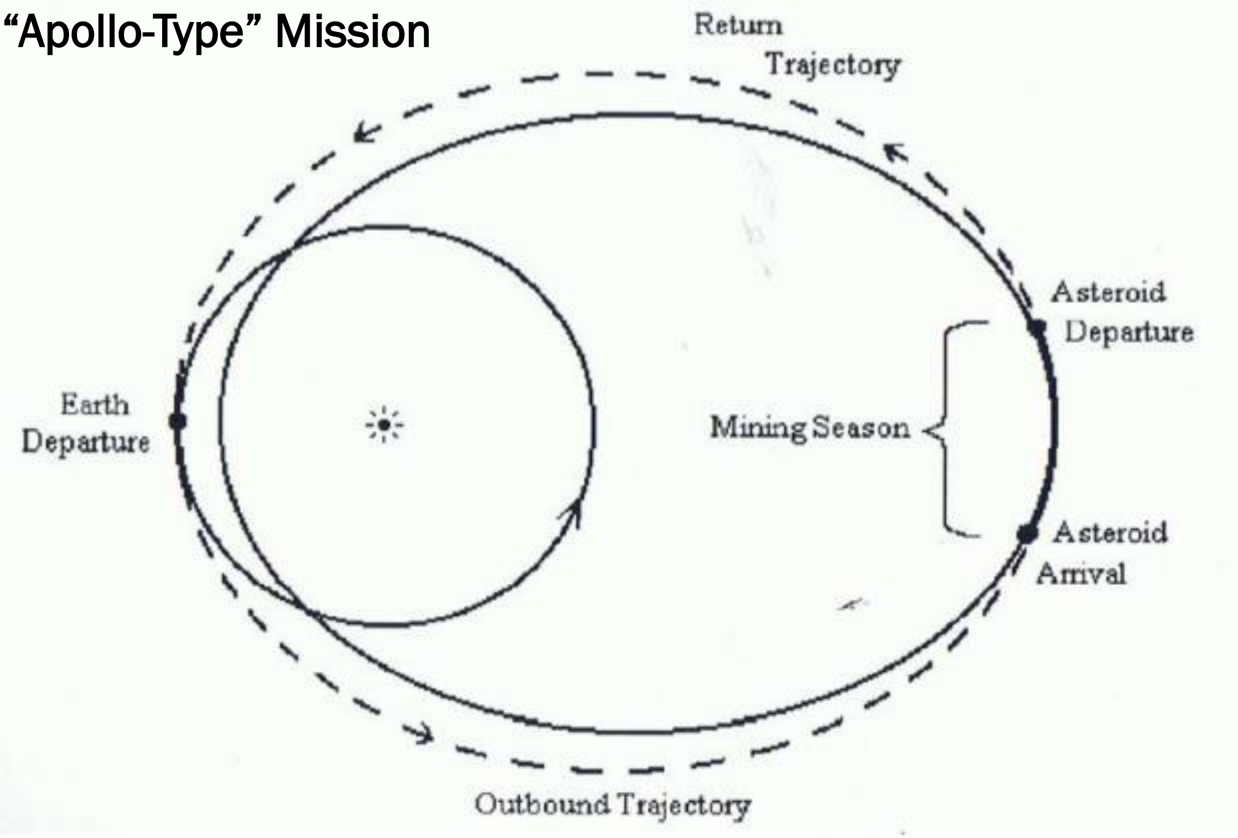


Image Credit: Sonter’s Thesis

LOW DELTA-VS FOR MANY NEAS

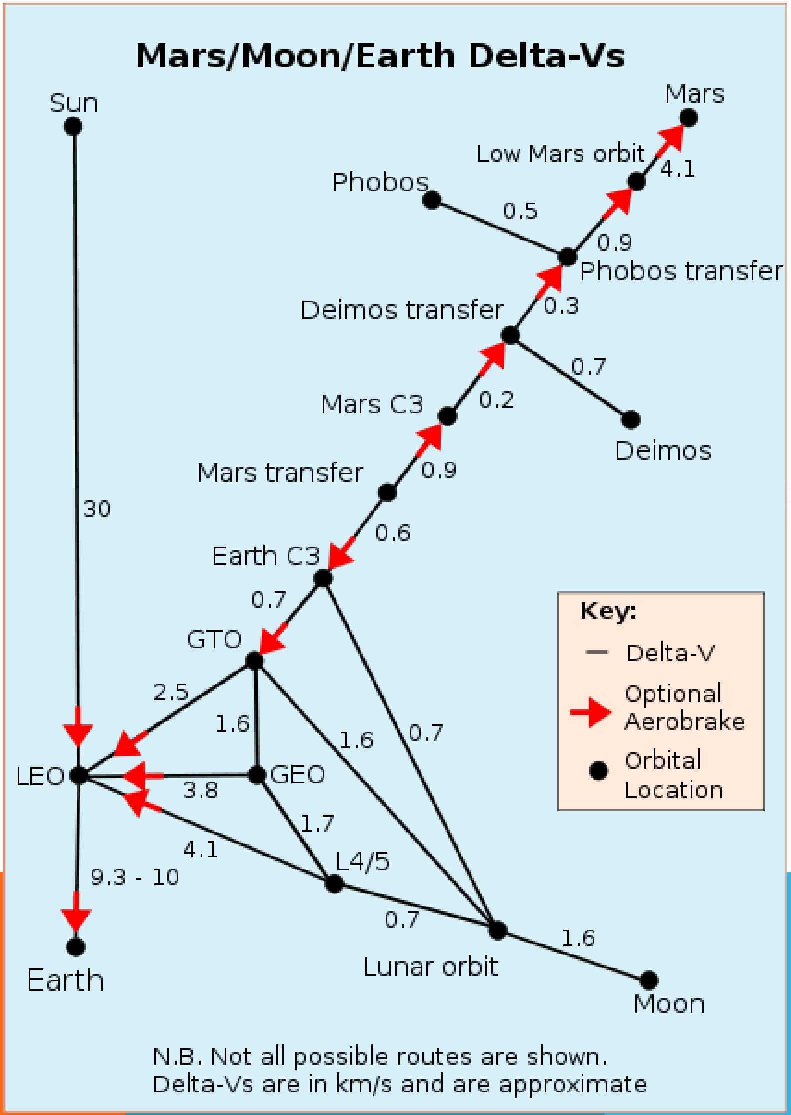
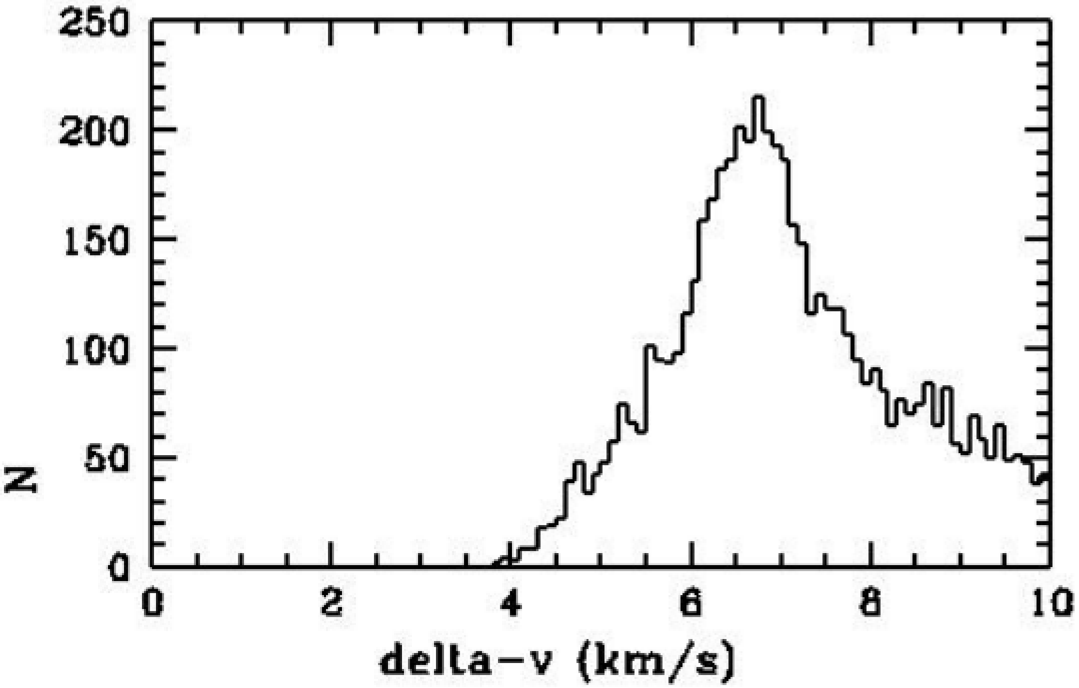


Image Credit: http://upload.wikimedia.org/wikipedia/commons/c/c9/Deltavs.svg



Compare!

Image Credit: Elvis, McDowell, Hoffman, and Binzel. “Ultra-low Delta-v Objects and the Human Exploration of Asteroids.”

ROCKET PROPULSION TECHNOLOGIES CLASSIFICATION

CHEMICAL PROPULSION

- Liquid Storable
- Liquid Cryogenic
- Solid
- Hybrid
- Cold Gas/Warm Gas

NON – CHEMICAL PROPULSION

- Electric propulsion
  - Resistojet
  - Ion thruster
  - Arcjet
  - Hall thruster
- Solar sail propulsion
- Thermal propulsion
- Pulsed plasma propulsion
- Magnetoplasmadynamic

MINING SYSTEM MODEL

Explorer

Rock Breaker

Excavator

Processor

MINING STEP 1: EXPLORER

- Explorer is a light fast robot equipped with a Rock Breaker and chemical analyzers that can scout viable mining areas.
- Low mobility environment prevents use of wheeled rover.

Locomotion Mode	Example	Feasibility	Location
Hopping	Jumping Tortoise, Ciliary Micro-hopper	High	Surface
Grasping	Rock Climber	High	Surface, Underground
Legged	Multi-limbed Rover, Big Dog	Medium	Surface

MINING STEP 1: EXPLORER EXAMPLES

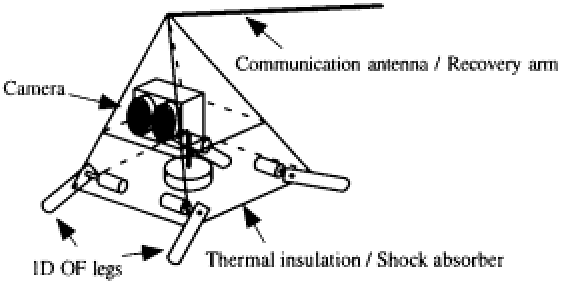


Image Credit: Yoshida. “Jumping Tortoise: A Robot Design for Locomotion on Micro Gravity Surface.”

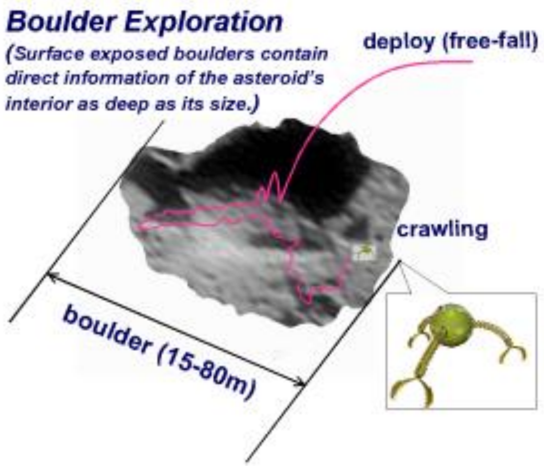
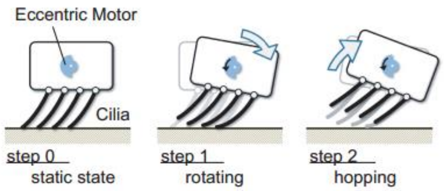


Image Credit: Yoshida, Maruki, and Yano. “A Novel Strategy for Asteroid Exploration with a Surface Robot.”



(a) Hopping based on reaction torque

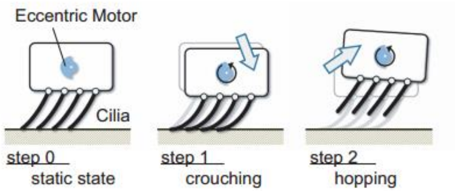


Image Credit: Nagaoka, et al. “Ciliary Micro-Hopping Locomotion of an Asteroid Exploration Robot.”

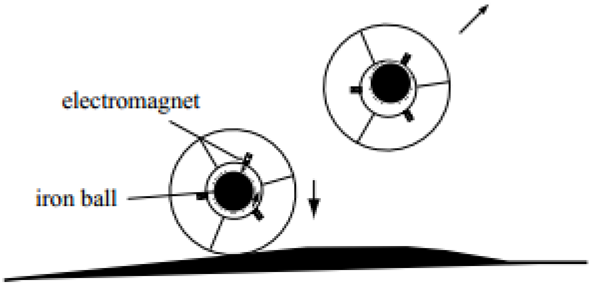


Image Credit: Nakamura, Shimoda, and Shoji. “Mobility of a Microgravity Rover using Internal Electromagnetic Levitation.”

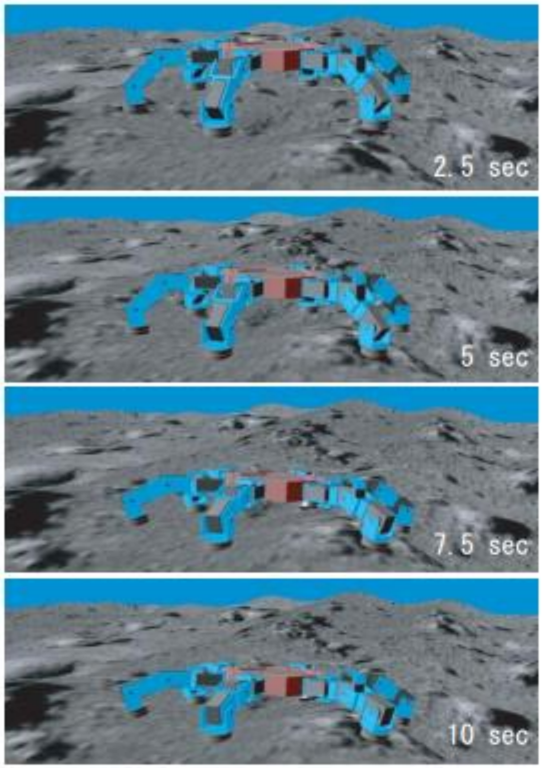
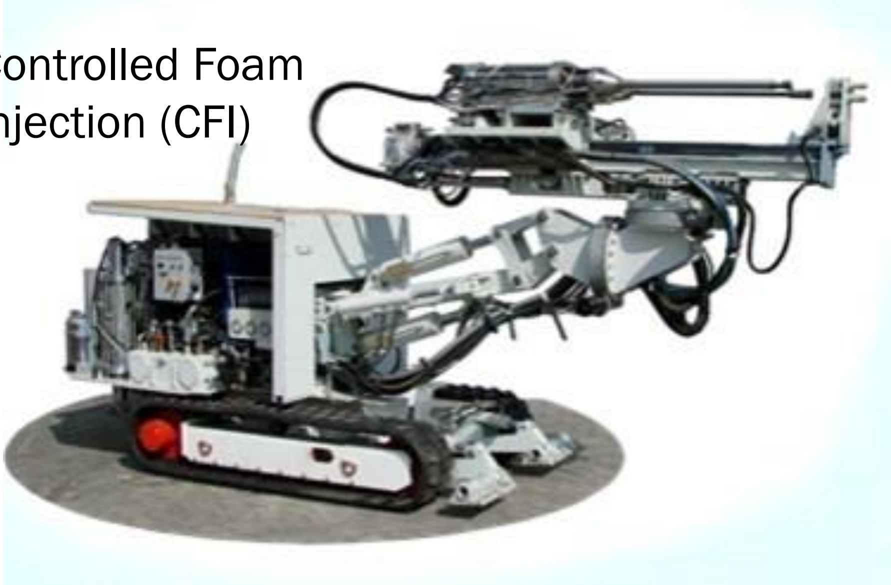


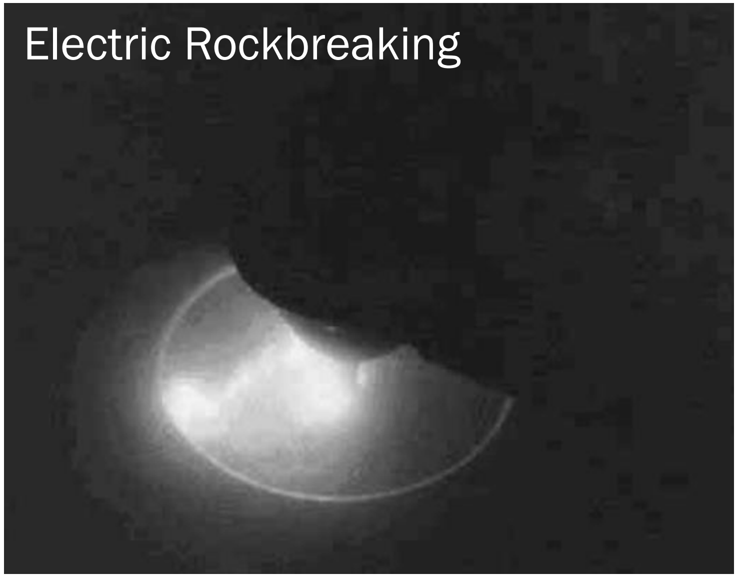
Image Credit: Chacin and Yoshida. “Multi-limbed Rover for Asteroid Surface Exploration using Static Locomotion.”

MINING STEP 2: ROCK BREAKER EXAMPLES

Controlled Foam Injection (CFI)



Electric Rockbreaking



Microwave Drilling

Diamond Wire Sawing

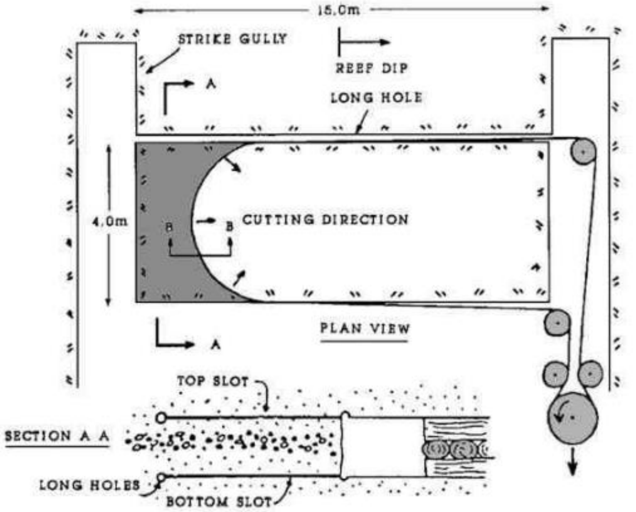


Image Credits: Harper, G.S. "Nederburg Miner."

MINING STEP 3A: ROCK EXCAVATOR

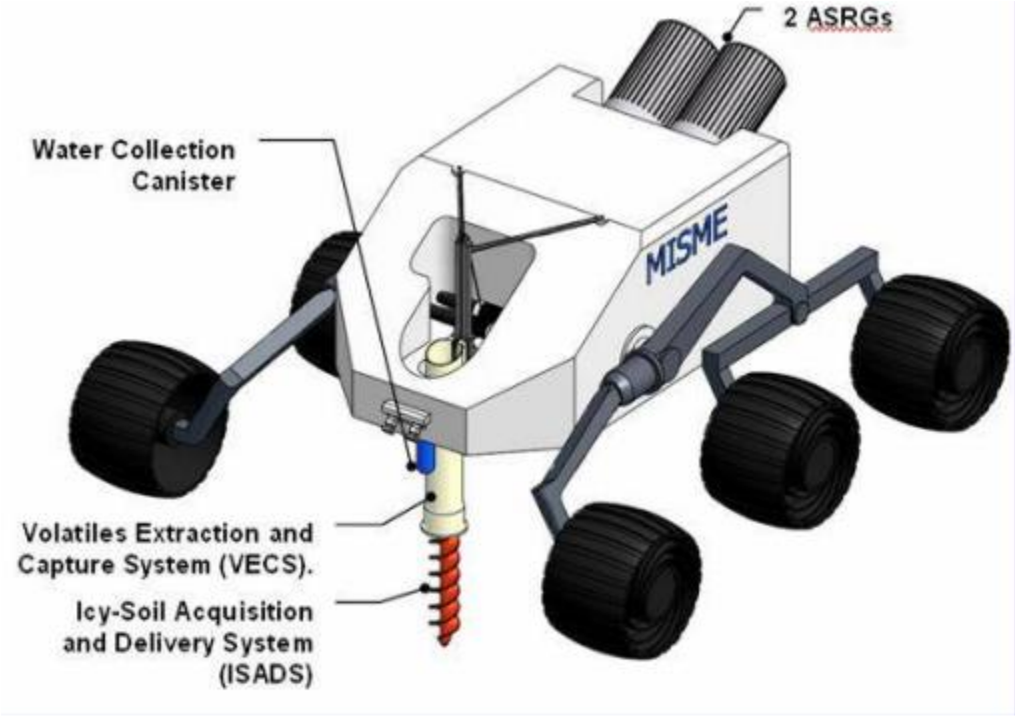
- The excavator digs up large quantities of rock in the area the Explorer + Rock Breaker has identified as viable. It is the main miner.
- Currently extremely common on Earth and there are robotic ones under development such as QinetiQ Spartacus:

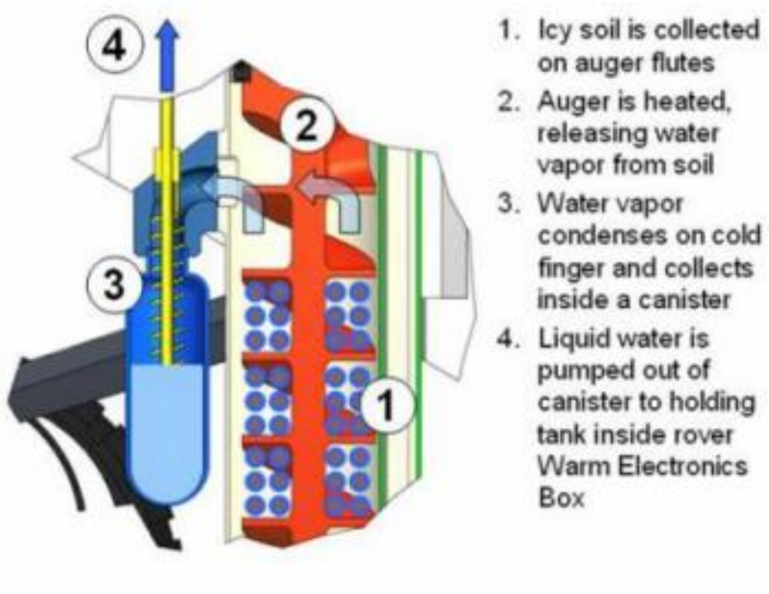
Parameter	Quantity
Capacity	4540 kg
Speed	2.33 m/s
Range	800 m
Power	Diesel
Volume	5.97 m^3
Mass	5675 kg

MINING STEP 3A:
ROCK EXCAVATOR EXAMPLE

QinetiQ Spartacus
Image Credits: QinetiQ

MINING STEP 3B: WATER EXTRACTOR





1. Icy soil is collected on auger flutes
2. Auger is heated, releasing water vapor from soil
3. Water vapor condenses on cold finger and collects inside a canister
4. Liquid water is pumped out of canister to holding tank inside rover Warm Electronics Box

Image Credits: Zacny et al. “Mobile In-situ Water Extractor (MISWE) for Mars, Moon, and Asteroids In Situ Resource Utilization.”

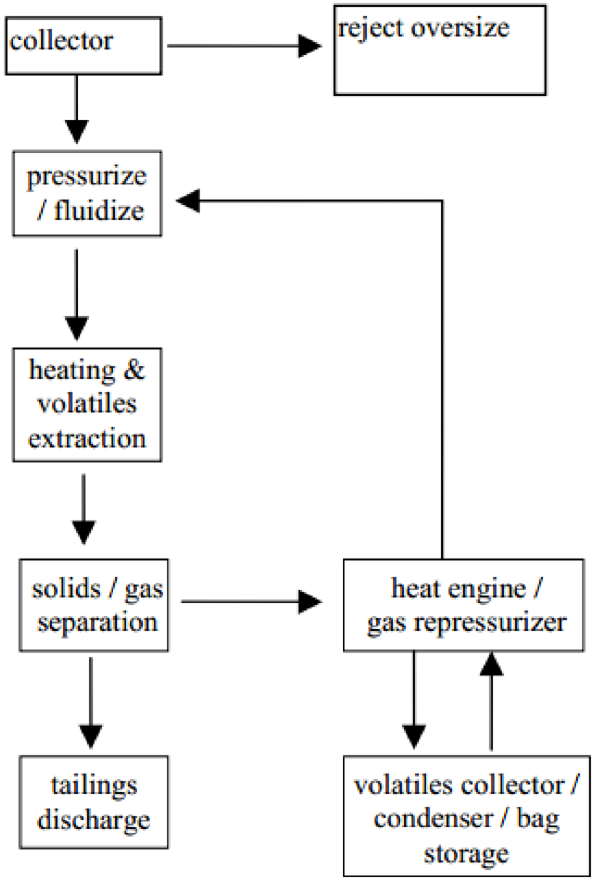
Water ice extraction from soils currently being developed by Honeybee called the Mars In-situ Water Extractor (MISWE).

MINING STEP 4: PROCESSOR

- Depending on the type of mineral or metal, processing it on-site may be more feasible than bringing it back to Earth.

Chemistry	Type	Technique
Metal	Loose grains Macroscopic lumps Interconnected dendrites	Electrostatic or magnetic separation Crush and then sieve Carbonyl separation
Volatiles	With minor silicates Minor component Chemically combined	Melt slabs Drill into, vaporize, distill Severe heating (> 800 K)
Hydrocarbons	With major silicates	Heat and distill

MINING STEP 4: PROCESSOR EXAMPLE



Conceptual process flow sheet for volatiles extraction from carbonaceous chondrite-type asteroid. Image Credit: Sonter, Mark. “Technical and Economic Feasibility of Mining the Near-Earth Asteroids.”

MINING SYSTEM DESIGN

	Robot	Qty	Subtot	Rock Breaker*	Qty	Subtot	Excavator	Qty	Subtot	Processor	Qty	Subtot	Total
Names	Microbot	100		N/A			N/A			N/A			
	iRobot 710 Warrior	3		Electric Rock-breaking	3		Generic	1		None			
Mass (kg)	0.1	100	10			0			0			0	
	226.8	3	680.4	0.5	3	1.5	453.5925	1	453.59	0	0	0	1145.493 kg
Carrying Mass (kg)	0	100	0			0			0	0	0	0	
	136.1	3	408.3	0	0	0	907.185	1	907.19	0	0	0	907.185 kg
Power (W)	0.1	100	10			0			0	0	0	0	
	500	3	1500	40000	3	120000	500	1	500	0	0	0	122000 W
Volume (m3)	4188.790205	100	418879			0			0	0	0	0	
	612553.045	3	2E+06	0.5	3	1.5	500	1	500	0	0	0	2257040 m^3

PHASES OF MINING

Phase I: Technology Development on Earth

Duration:
5 years

Goals: Development and manufacturing of necessary equipment

Phase II: Infrastructure Setup in Space

Duration:
5 years

Goals: Establish an operation base in space; Send mining module to target asteroid; Send cargo module to target asteroid

Phase III: Mining Initialization (Reconnaissance)

Duration:
3 years

Goals: Initialize mining process

Phase IV: Manufacturing and Consumption

Duration:
3 years

Goals: Continue mining process; Sell the product

COST STRUCTURE

	Phase I	Phase II	Phase III	Phase IV
R & D				
Target Analysis	x			
Technology Analysis	x			
Space Craft Design	x			
Manufacture Space Craft Model	x			
Qualification Tests	x			
Optimizing Space Crafts / Mining Technology	x	x	x	x
Manufacturing and Testing				
Manufacture Docking Station	x			
Manufacture Mining Module	x			
Manufacture Cargo Module	x			
Launch				
Launch Docking Station		x		
Launch Mining Module		x		
Launch Cargo Module		x		
Operations				
Costs for Control Center (own or rent)		x	x	x
Personnel Cost		x	x	x
Administration and Project Management				
Project Management	x	x	x	x
Administration	x	x	x	x

RESOURCES UTILIZATION BY PHASES

		Sell in				
Commodities and Services	**Processed commodity**	**Phase I**	**Phase II**	**Phase III**	**Phase IV**	**Problem**
Water	unprocessed	×	×	×	✓	Should be possible in near future
	Water for life support	×	×	×	✓	Should be possible in near future
	Food	×	×	×	×	We need our own space farm
	Fuel (H2, O2, CH4)	×	×	×	✓	Should be possible in near future
Construction metals (Fe / Ni / Ti)	unprocessed (Ore)	×	×	×	✓	Implys space industry
	processed in bares	×	×	×	✓	We need space our own kind of space factory
	construction elements	×	×	×	×	Implys space industry
Pt group metals	unprocessed (Ore)	×	×	×	✓	Implys space industry
	pure in bars	×	×	×	✓	Implys space industry
	PtG containing products	×	×	×	×	Implys space industry
Rare Earth elements	unprocessed	×	×	×	✓	Implys space industry
	pure for industry use	×	×	×	✓	Implys space industry
Silicates	unprocessed (Ore)	×	×	×	✓	Implys space industry
	processed as mono-crystal	×	×	×	×	Implys space industry
	Si containing products	×	×	×	×	Implys space industry
Carbon and its chemical compounds	unprocessed	×	×	×	✓	Implys space industry
Space tourism (hotel)		×	✓	✓	✓	We have to offer just accomodation in order to avoid futher costs caused by launches.
Science capacities		×	✓	✓	✓	We have to calculate appropriate rooms / laboratories in our space station.
Space jewelry collection		×	×	✓	✓	Should be possible in near future. We should sell limited editions exclusively in space (for the rich tourists) -> we can ask for extremly high price.

NET PRESENT VALUE

- The economic justification for an asteroid mining operation is only the case if the net present value (NPV) is above zero.
- It is NOT just the cost of the project and revenue generated.

SONTER'S NPV EQUATION

$$\mathrm{NPV} = C_{orbit}\, M_{mpe}\, f\, t\, r\, e^{-\Delta v/v_e}\, (1+i)^{-a^{3/2}} - \left(C_{manuf}\, (M_{mpe} + M_{ps} + M_{ic}) + B\, n\right)$$

C_{orbit} is the per kilogram Earth-to-orbit launch cost [$/kg]

M_{mpe} is mass of mining and processing equipment [kg]

f is the specific mass throughput ratio for the miner [kg mined / kg equipment / day]

t is the mining period [days]

r is the percentage recovery of the valuable material from the ore

Δv is the velocity increment needed for the return trajectory [km/s]

v_e is the propulsion system exhaust velocity [km/s]

i is the market interest rate

a is semi-major axis of transfer orbit [AU]

M_{ps} is mass of power supply [kg]

M_{ic} is mass of instrumentation and control [kg]

C_{manuf} is the specific cost of manufacture of the miner etc. [$/kg]

B is the annual budget for the project [$/year]

GE AND SATAK NPV

$NPV = P - C_M - C_L - C_R - C_E$, where

P = returned profit ($)

C_M = Manufacturing cost ($)

C_L = Launch cost ($) is equal to $m_{s/c}$ (mass of spacecraft) * u_{LV} (unit mass cost)

C_R = Recurring cost ($) is equal to B (annual operational expense) * T (total time)

C_E = Reentry cost ($) is equal to $M_{returned}$ (mass returned) * f_e (fraction of material sold on Earth) * u_{RV} (unit mass cost)

$$C_M = C_{miner} + C_{spacecraft}$$

$$C_{miner} = M_{mpe} u$$

$$P = \frac{[V_s(1 - f_e) + V_e f_e] M_{returned}}{(1 + i)^T}$$

$$C_{s/c} = 10^6 (225 + \frac{M_{mpe} p_f}{8})$$

$$p_f = \frac{e^{-\Delta v_t / v_e} - s_f}{1 - s_f}$$

where,

Vs = Value in space ($)

Ve = Value on Earth ($)

f_e = Fraction of material sold on Earth

where,

u = unit cost of miner ($/kg)

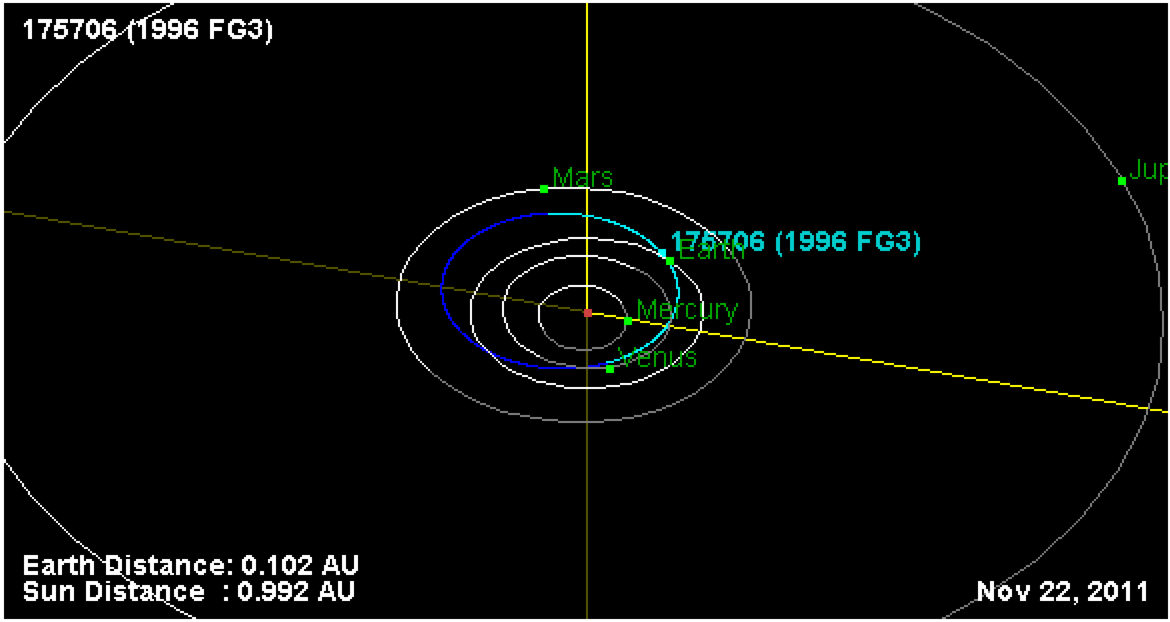
p_f = payload fraction

s_f = structural fraction

Δv_t = delta-v to asteroid

v_e = exhaust velocity

EXAMPLE CASE:
1996 FG3

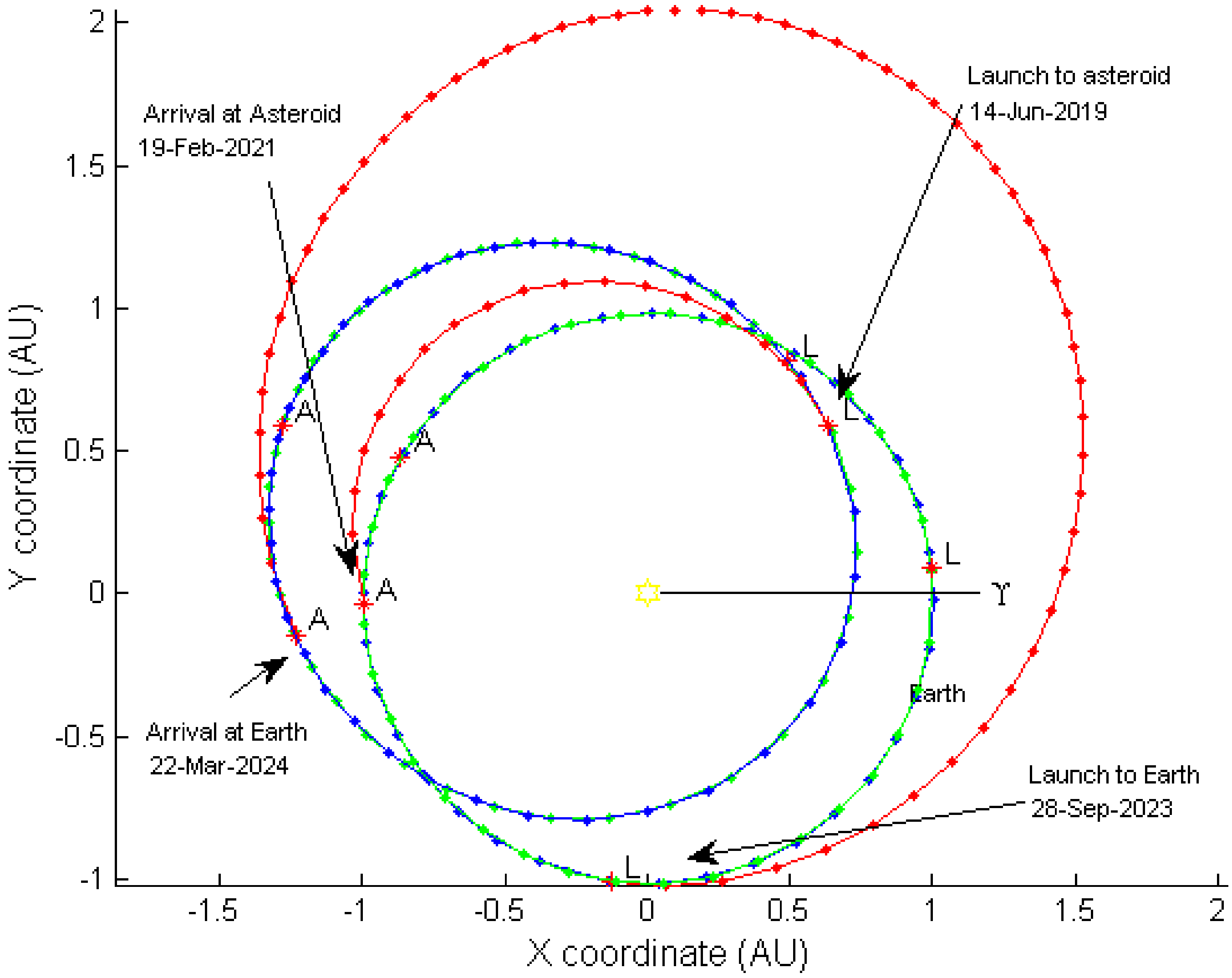


Source: NASA JPL

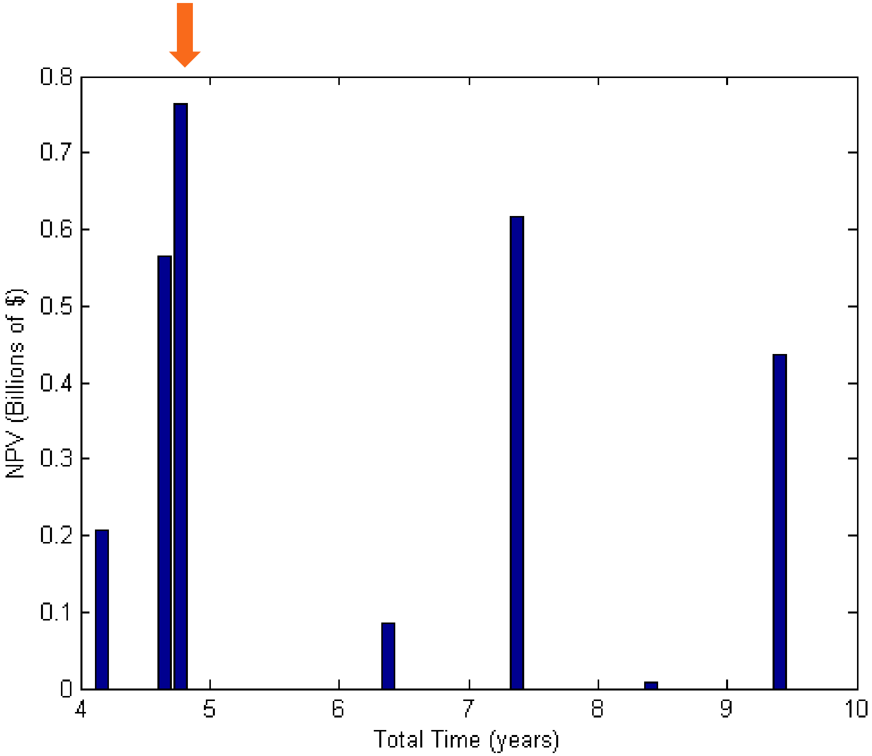
Preliminary baseline of ESA's MarcoPolo-R Mission

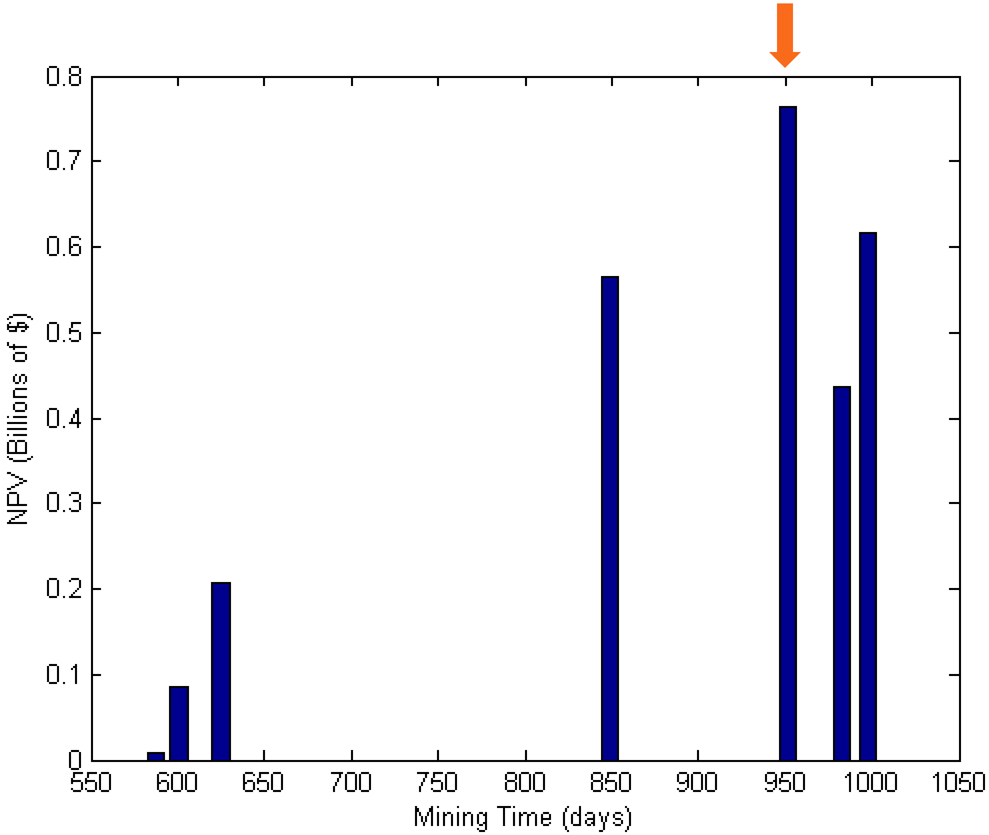
Element	Value	Uncertainty (1-sigma)	Units
e	.3498340666887911	1.5696e-08	
a	1.054167926597945	7.8388e-10	AU
q	.6853840738632947	1.6408e-08	AU
i	1.991740620771903	1.4433e-06	deg
node	299.7309666180939	4.8879e-05	deg
peri	23.98117617336174	4.8216e-05	deg
M	167.6713320688418	1.4068e-06	deg
t_p	2456216.372168471335 (2012-Oct-15.87216847)	1.4204e-06	JED
period	395.3330514670441 1.08	4.4095e-07 1.207e-09	d yr
n	.910624595297746	1.0157e-09	deg/d
Q	1.422951779332595	1.0581e-09	AU

TRAJECTORY TO 1996 FG3



NPV COMPARISONS

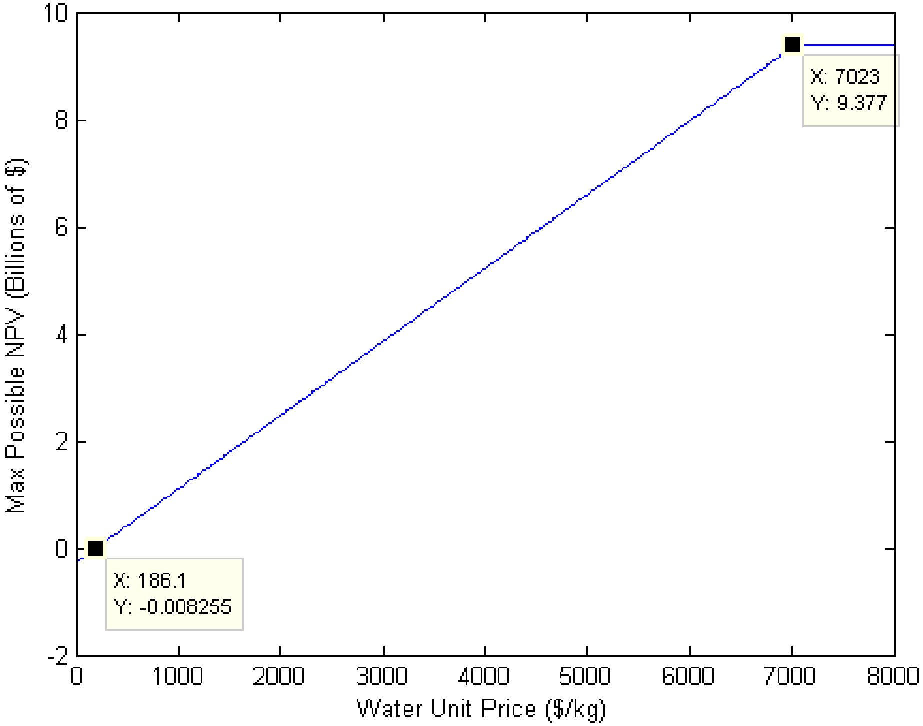


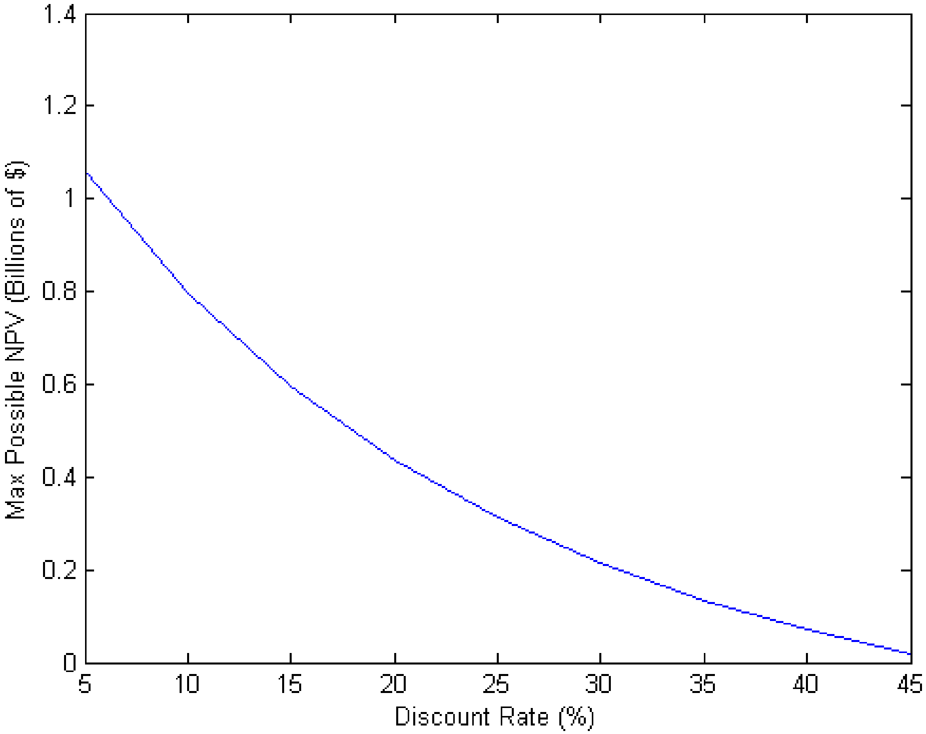


- Selling water at $200.00 per liter (kg) yields a NPV of $763,370,000.

- Both mining time and total time for is optimized for maximum returns.
  - Greatest mining time ≠ best NPV
  - Least total time ≠ best NPV

NPV DEPENDENCY ON ECONOMICS

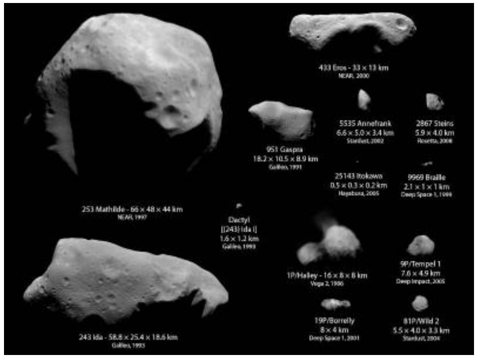




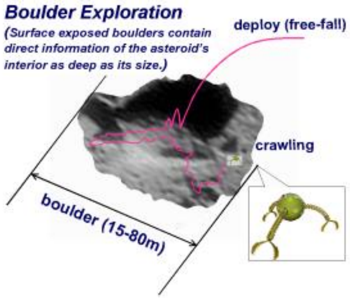
- Selling water at a minimum of 187 USD/kg is necessary to break even.
- Even bringing back water to sell at **$7000/kg** makes a profit since launching >1500 kg of water is very expensive.

- A good estimate of discount rate is crucial for estimating a good NPV.

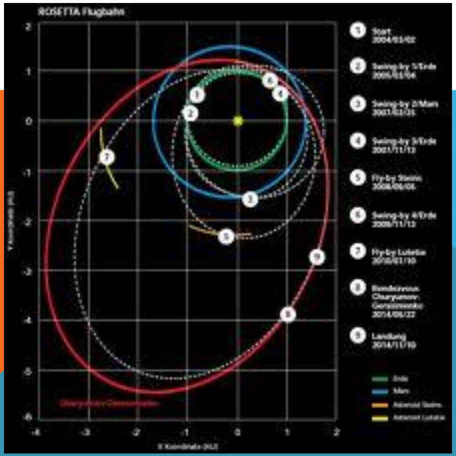
WHAT’S NEXT?


433 Eros - 33 × 13 km
NEAR, 2000
5535 Annefrank
6.6 × 5.0 × 3.4 km
Stardust, 2002
2867 Steins
5.9 × 4.0 km
Rosetta, 2008
951 Gaspra
18.2 × 10.5 × 8.9 km
Galileo, 1991
25143 Itokawa
0.5 × 0.3 × 0.2 km
Hayabusa, 2005
9969 Braille
2.1 × 1 × 1 km
Deep Space 1, 1999
253 Mathilde - 66 × 48 × 44 km
NEAR, 1997
Dactyl
[(243) Ida I]
1.6 × 1.2 km
Galileo, 1993
1P/Halley - 16 × 8 × 8 km
Vega 2, 1986
9P/Tempel 1
7.6 × 4.9 km
Deep Impact, 2005
19P/Borrelly
8 × 4 km
Deep Space 1, 2001
81P/Wild 2
5.5 × 4.0 × 3.3 km
Stardust, 2004
243 Ida - 58.8 × 25.4 × 18.6 km
Galileo, 1993


T190


Boulder Exploration
(Surface exposed boulders contain direct information of the asteroid’s interior as deep as its size.)
deploy (free-fall)
crawling
boulder (15-80m)


SPACE MINERS


ROSETTA Flugbahn
1 Start 2004/03/02
2 Swing-by 1/Erde 2005/03/04
3 Swing-by 2/Mars 2007/02/25
4 Swing-by 3/Erde 2007/11/13
5 Fly-by Steins 2008/09/05
6 Swing-by 4/Erde 2009/11/13
7 Fly-by Lutetia 2010/07/10
8 Rendezvous Churyumov-Gerasimenko 2014/05/22
9 Landung 2014/11/10
Erde
Mars
Asteroid Steins
Asteroid Lutetia
Churyumov-Gerasimenko
X Koordinate (AU)
Y Koordinate (AU)
2
1
0
-1
-2
-3
-4
-5
-6
-4
-3
-2
-1
0
1
2

QUESTIONS?

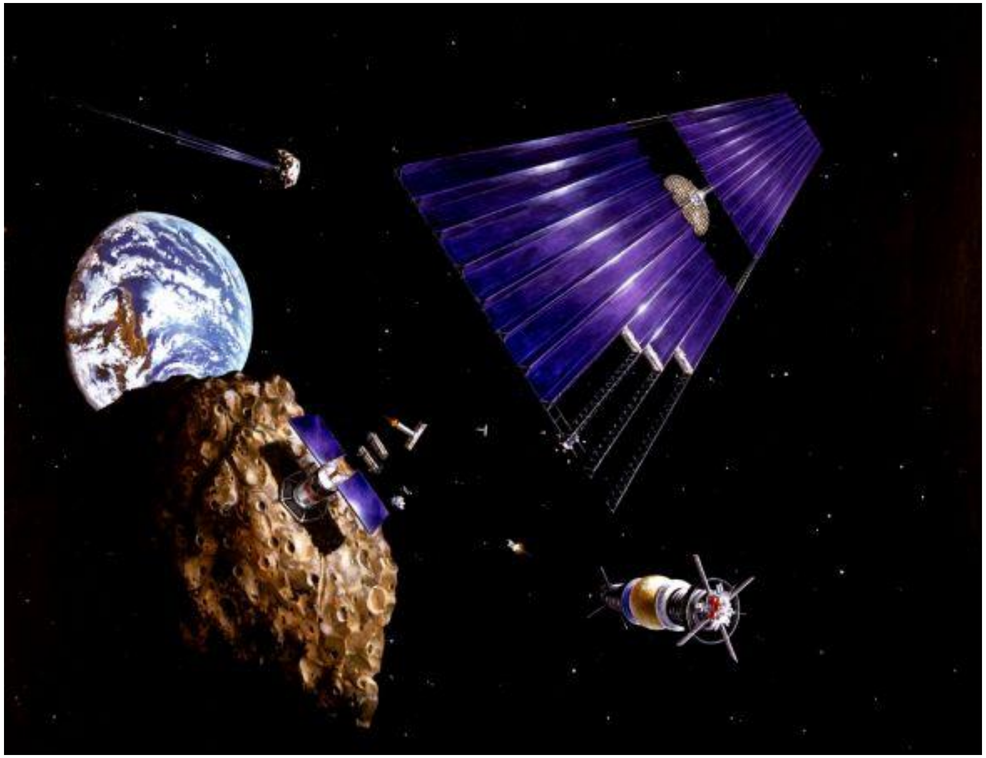


Image Credit:
http://en.es-static.us/upl/2012/04/asteroid_mining.jpeg