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THE TECHNOLOGICAL AND ECONOMIC FEASIBILITY OF ASTEROID MINING

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THESIS

THE TECHNOLOGICAL AND ECONOMIC FEASIBILITY OF ASTEROID MINING

by

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June 2021

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13. ABSTRACT (maximum 200 words)

The objective of this thesis is to determine the technological and economic feasibility of asteroid mining. This thesis elaborates on why the key technological development should be further developing water extraction and manufacturing techniques. This secondary research was conducted with a survey of the technical and economic conclusions of many books, conference papers, and journal articles. Even though a mobile in-situ water extractor has demonstrated water extraction capabilities, the technology is not yet ready to be utilized in an actual asteroid mining architecture in the harsh climates of outer space. This thesis concludes that asteroid mining will be technologically feasible but will only be economically feasible upon further refinement of water manufacturing techniques on celestial bodies. This thesis recommends further investment into water extraction and manufacturing techniques from commercial companies and the government in order to increase the economic viability of asteroid mining.

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THE TECHNOLOGICAL AND ECONOMIC FEASIBILITY OF ASTEROID MINING

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

The objective of this thesis is to determine the technological and economic feasibility of asteroid mining. This thesis elaborates on why the key technological development should be further developing water extraction and manufacturing techniques. This secondary research was conducted with a survey of the technical and economic conclusions of many books, conference papers, and journal articles. Even though a mobile in-situ water extractor has demonstrated water extraction capabilities, the technology is not yet ready to be utilized in an actual asteroid mining architecture in the harsh climates of outer space. This thesis concludes that asteroid mining will be technologically feasible but will only be economically feasible upon further refinement of water manufacturing techniques on celestial bodies. This thesis recommends further investment into water extraction and manufacturing techniques from commercial companies and the government in order to increase the economic viability of asteroid mining.

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LIST OF ACRONYMS AND ABBREVIATIONS

ACR	Asteroid Capture and Return
AIAA	American Institute of Aeronautics and Astronautics
ALTWG	Altimetry Working Group
AMICA	Telescopic Camera
APL	Applied Physics Laboratory
AU	Astronautical Unit
Caltech	California Institute of Technology
CaO	calcium oxide
COVID-19	Coronavirus Disease 2019
JPL	Jet Propulsion Laboratory
kg	kilogram
km	kilometer
LEO	Low Earth Orbit
ESA	European Space Agency
FC	Framing Camera
FeO	iron oxide
IR	infrared
ISRU	In-Situ Resource Utilization
ISS	International Space Station
JAXA	Japan Aerospace Exploration Agency
H_2O	water
ISR	intelligence, surveillance, reconnaissance
K_2O	potassium oxide
KISS	Keck Institute for Space Studies
kW	kilowatt
LIDAR	Light Detection and Ranging
m	meter
MAG	Magnetometer
MgO	magnesium oxide
MINERVA	Micro/Nano Experimental Robot Vehicle for Asteroid

MIRO	Microwave Instrument for the *Rosetta* Orbiter
MSI	Multispectral Imager
MSolo	Mass Spectrometer Observing Lunar Operations
Na_2O	sodium oxide
NASA	National Aeronautics and Space
NFT	Natural Feature Tracking
NEA	Near-Earth Asteroid
NEAR	Near Earth Asteroid Rendezvous
NEO	Near-Earth Object
NIMS	Near Infrared Mapping Spectrometer
NIRVSS	Near-Infrared Volatiles Spectrometer System
NIS	Near Infrared Spectrometer
NSS	Neutron Spectrometer System
OMB	U.S. Office of Management and Budget
ONC-W	Wide-view Camera
OSIRIS	Optical, Spectroscopic, and Infrared Remote Imaging System
OSIRIS-REx	Origins, Spectral Interpretation, Resource Identification, Security and Regolith-Explorer
OST	Outer Space Treaty
P_2O_5	phosphorous oxide
psia	pounds per square inch absolute
PGM	Platinum Group Metal
RCP	*Rosetta* Plasma Consortium
ROMAP	*Rosetta* Lander Magnetometer and Plasma Monitor
RTG	Radioisotope Thermal Generators
SPD	Space Policy Directive
SRC	Sample Return Capsule
SiO_2	silicon dioxide
SSI	Solid-State Image
TAG	Touch-and-Go
TAGSAM	Touch-and-Go Sample Acquisition Mechanism
TRIDENT	The Regolith and Ice Drill for Exploring New Terrains

TiO_2	titanium dioxide
USD	United States Dollar
VIR	Visible and Infrared Spectrometer
VIRTIS	Visible and Infrared Thermal Imaging Spectrometer
XRS	X-Ray Fluorescence Spectrometer

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ACKNOWLEDGMENTS

I love looking up at the night sky. Some might consider staring into a blank, black canvas sprinkled with twinkling lights a waste of time, but I find solace in my daily walk. Every night at 10 PM, I hear my roommate close his door as he winds down for the night, cueing me to step outside into the brisk, breezy night. As I make the two-minute trek to my favorite tree, sit down, and look up into the night sky, I take a sigh of relief realizing how infinitely small we all are in the universe.

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I. INTRODUCTION

A. BACKGROUND, RESEARCH QUESTION SIGNIFICANCE AND OBJECTIVES

In 1996, John S. Lewis wrote in his book *Mining the Sky: Untold Riches from the Asteroids, Comets, and Planets*,

> The truth is that the resources available to us are, for all practical purposes, infinite. Building on what we know of the solar system, and using presently available or readily foreseeable technologies, we can relieve earth of its energy problem, make astronomical amounts of raw materials available, and raise the living the standard of people worldwide. We only need to lift up our eyes and look at the wealth of energy and materials that surrounds us in space. That vision will inspire us to seek out ways to make economical use of them.[1]

There is a new awakening to space. Humanity is awakening to the enormous possibilities that space and celestial bodies have to offer. The United States has established a Space Force and the military relies heavily on space for communications, imagery, intelligence, surveillance and reconnaissance (ISR), weather tracking, position, navigation and timing (PNT), and much more. The push toward a green new agenda has catalyzed a demand for sustainable energy. Even the United States' $3 trillion budget deficit has added pressure to provide an international good or service to help relieve this tremendous economic burden.[2] Simply put, there is a new race for space.

The possibility to exploit this largely unexplored domain via asteroid mining has been discussed for decades. Conclusions have ranged from not economically viable to economically viable under optimistic circumstances.

The objective of this thesis is to explore and analyze the technological and economic feasibility of conducting asteroid mining operations. The results of this analysis of asteroid mining operations provide a strong rationale that the focus of future research

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[1] John S. Lewis, *Mining the Sky: Untold Riches from the Asteroids, Comets, and Planets* (New York: Helix Book, 1997), xi.

[2] "U.S. Debt Clock," U.S. Debt Clock, accessed May 3, 2021, https://usdebtclock.org/.

should be refining the technology to extract and process water from the Moon and Near-Earth Asteroids (NEA).

B. METHODOLOGY

Before exploring past space exploration missions or technological and economic feasibility studies, a foundation of how to characterize NEAs must first be established. The common vernacular, terms, and definitions of the asteroid mining domain must all be defined before attempting to determine the technological and economic feasibility of asteroid mining. Once this framework is established, only then can one properly begin to examine past space exploration missions, asteroid mining missions, and technological and economic feasibility studies. Section I.C establishes framework from which this thesis can attempt to tackle this task.

Section I.D, the literature review, summarizes the general conclusions from the body of existing asteroid mining feasibility research, commonalities and disagreements between authors and the conclusions derived from their studies, and finally what research gaps exist. This enables us to properly scope our contribution to the existing body of knowledge regarding the technical, economic, and political viability of asteroid mining.

Next, a survey of past space exploration missions is provided in Chapter II. This chapter will not specifically include asteroid mining missions as that will be covered in detail in the Chapter III. This brief overview examines technologies utilized during past space missions such as those used to characterize NEAs.

Chapter III surveys past sample return missions, the technologies utilized, and any lessons learned from those missions.

The examination of asteroid mining technologies and feasibility occurs in Chapter IV. Key technologies that have made past sample return missions possible will be examined. Technologies developed for the Moon will also be examined as these technologies may help future asteroid mining missions.

The economic feasibility of asteroid mining will be examined in Chapter V. We will examine the cost of previous sample return missions, as well as the cost of other various types of mining operations.

Finally, the conclusion provides current and future applications relevant to the government sector and the commercial industry. Key technological and economic issues will be offered for future research topics.

C. CHARACTERIZATION OF NEAR-EARTH ASTEROIDS

1. Types and Composition of NEAs

Near Earth Asteroids (NEAs) are classified as asteroids whose "closest approach to the Sun is less than 1.3 Astronomical Units" (AU).[3] Spectroscopic studies from meteorites and spectral taxonomies of asteroids have revealed three main categories of NEAs: C-type, S-type, and M-type.[4] C-type (carbonaceous) asteroids are defined as "water-bearing with very high contents of opaque, carbonaceous material."[5] S-type (stony) asteroids are "anhydrous and rocky, consisting of silicates, sulphides, and metals."[6] M-type (metallic) asteroids "exhibit high radar reflectivity characteristic of metals."[7]

The ability to characterize the type of asteroid is important to the overall mission objective. For instance, C-type asteroids are the most promising type of asteroid; they potentially contain the most useful resources to future astronauts and spacecraft for spacefaring missions and make up approximately 20% of known NEAs.[8] The usefulness of C-type asteroids is due to the relatively higher concentration of water that can have

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[3] Massimiliano Vasile and Edmondo Minisci, eds., *Asteroid and Space Debris Manipulation: Advances from the Stardust Research Network* (Reston, VA: American Institute of Aeronautics and Astronautics, Inc., 2016), xiii, https://doi.org/10.2514/4.103247.

[4] Charles L. Gerlach, "Profitably Exploiting Near-Earth Object Resources," in *2005 International Space Development Conference* (Washington, DC: National Space Society, 2005), 7–8.

[5] Gerlach, 8.

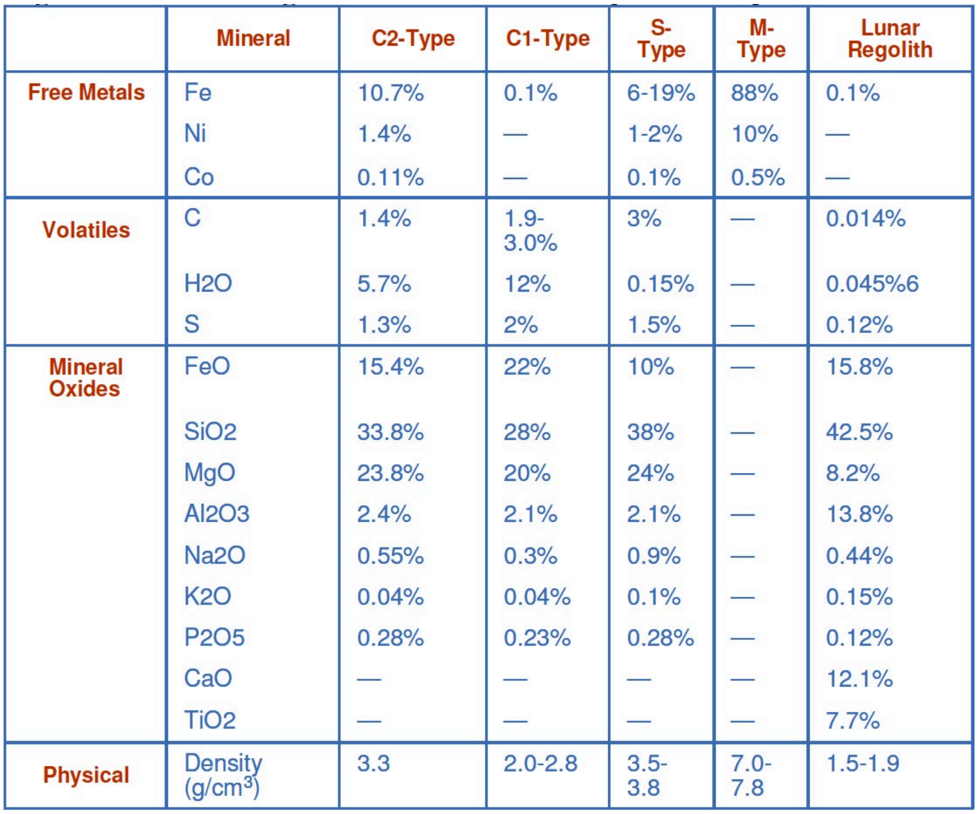
[6] Gerlach, 8.

[7] Gerlach, 8.

[8] John Brophy et al., "Asteroid Retrieval Feasibility Study" (Keck Institute for Space Studies, April 2, 2012), 16.

various spacefaring uses including, but not limited to, life sustainment, propellant, radiation shielding, and agriculture. The most prominent free metal in C-type asteroids is iron (Fe). Water (H_2O) is the most common volatile, "a substance that is readily vaporizable at relatively low temperatures," in C1-type and C2-type asteroids.[9] Other mineral oxides include iron oxide (FeO), silicon dioxide (SiO_2), magnesium oxide (MgO), aluminum oxide (Al_2O_3), sodium oxide (Na_2O), potassium oxide (K_2O), phosphorus pentoxide (P_2O_5), calcium oxide (CaO), and titanium dioxide (TiO_2). Gerlach provided estimated composition percentages and further characterization of these asteroid types, shown in Table 1.

Table 1. Mineralogical, Chemical, and Physical Properties of Asteroids[10]



	Mineral	C2-Type	C1-Type	S-Type	M-Type	Lunar Regolith
Free Metals	Fe	10.7%	0.1%	6-19%	88%	0.1%
	Ni	1.4%	—	1-2%	10%	—
	Co	0.11%	—	0.1%	0.5%	—
Volatiles	C	1.4%	1.9-3.0%	3%	—	0.014%
	H2O	5.7%	12%	0.15%	—	0.045%6
	S	1.3%	2%	1.5%	—	0.12%
Mineral Oxides	FeO	15.4%	22%	10%	—	15.8%
	SiO2	33.8%	28%	38%	—	42.5%
	MgO	23.8%	20%	24%	—	8.2%
	Al2O3	2.4%	2.1%	2.1%	—	13.8%
	Na2O	0.55%	0.3%	0.9%	—	0.44%
	K2O	0.04%	0.04%	0.1%	—	0.15%
	P2O5	0.28%	0.23%	0.28%	—	0.12%
	CaO	—	—	—	—	12.1%
	TiO2	—	—	—	—	7.7%
Physical	Density (g/cm^3)	3.3	2.0-2.8	3.5-3.8	7.0-7.8	1.5-1.9

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[9] "Volatile," in *Merriam-Webster*, accessed February 24, 2021, https://www.merriam-webster.com/dictionary/volatile.

[10] Source: Gerlach, "Profitably Exploiting Near-Earth Object Resources," 8.

Furthermore, the density and porosity, a unitless ratio of the void volume to the total volume, of spherical asteroids can be observed and measured. Amplifying details regarding grain density, bulk density, and porosity are described as follows:

> For common rock-forming minerals, the crystal structures, lattice volumes, and elemental compositions are well defined, so the densities of geologic materials common in asteroids are similarly well defined…These densities refer to a grain density, which is the mass of an object divided by the volume occupied only by mineral grains. This is the average density of the solid portions of a rock. The density value returned by spacecraft measurements is bulk density, which is the mass of an object divided by its volume (including the volume of its pore spaces). The ratio between grain and bulk density is the porosity, the percentage of the bulk volume of a rock that is occupied by empty space. Porosity can be a major component of asteroid volume, and some porosity is found in most meteorites.[11]

Figure 1 illustrates the estimated mass, diameter, and bulk densities of various NEAs. The first three asteroids in Figure 1 are Ceres, Pallas, and Vesta. These NEAs are the first, second, and third most massive objects in the asteroid belt, respectively, and are all classified as dwarf planets.[12] While the mass and diameter of most NEAs vary greatly, their bulk densities range from 0.96 to 3.44 g/cm^3.

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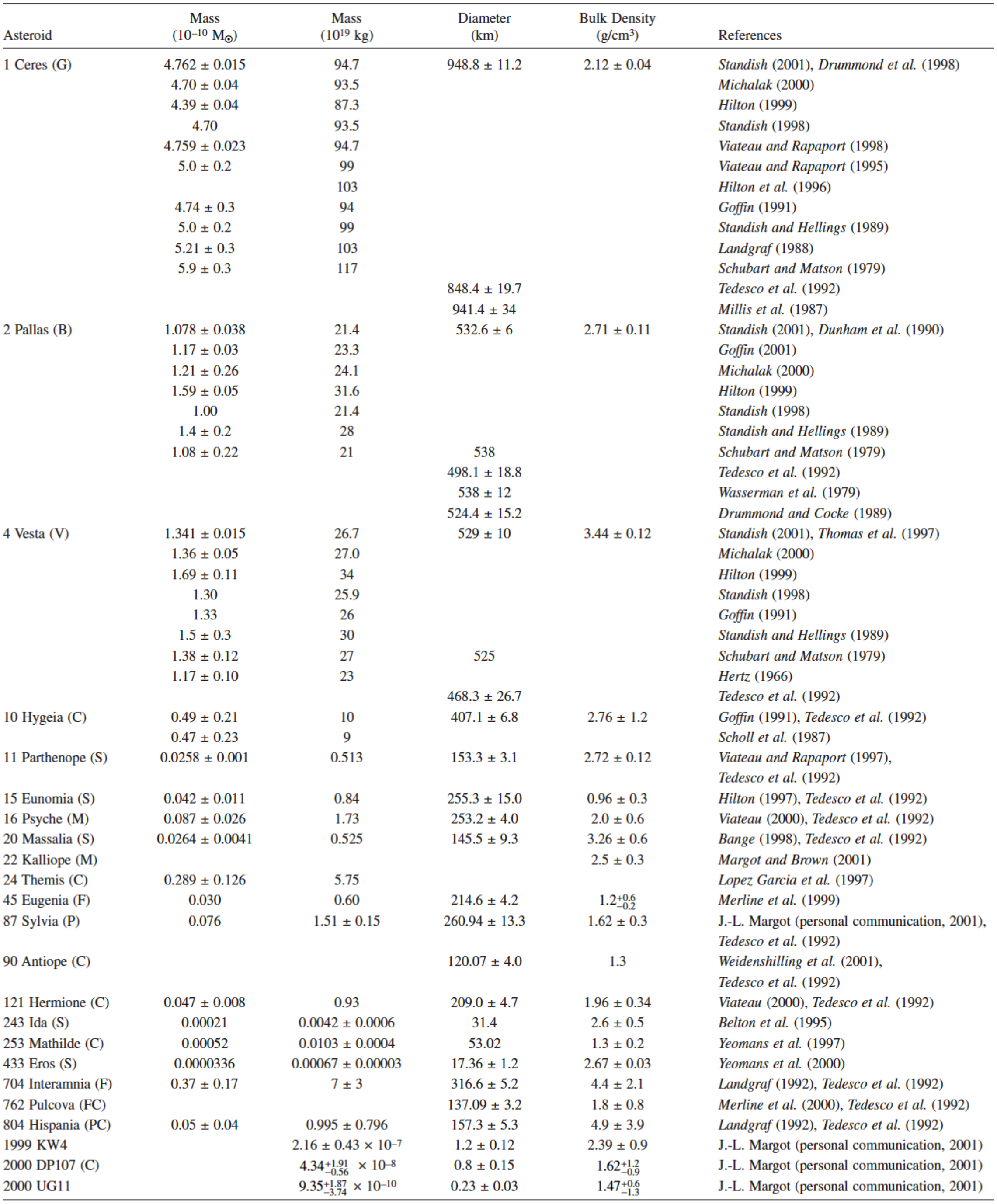
[11] D. T. Britt et al., "Asteroid Density, Porosity, and Structure," *Asteroids III*, 2002, 485.

[12] Nola T. Redd, "Ceres: The Smallest and Closest Dwarf Planet," Space.com, May 23, 2018, https://www.space.com/22891-ceres-dwarf-planet.html; Charles Q. Choi and 2020, "Massive Asteroid Pallas Has a Violent, Cratered Past, Study Reveals," Space.com, February 11, 2020, https://www.space.com/asteroid-pallas-craters-violent-history.html; Nola T. Redd, "Vesta: Facts About the Brightest Asteroid," Space.com, May 29, 2018, https://www.space.com/12097-vesta-asteroid-facts-solar-system.html.



Asteroid	Mass (10^{-10} $M_\odot$)	Mass (10^{19} kg)	Diameter (km)	Bulk Density (g/cm^3)	References
1 Ceres (G)	4.762 ± 0.015	94.7	948.8 ± 11.2	2.12 ± 0.04	*Standish* (2001), *Drummond et al.* (1998)
	4.70 ± 0.04	93.5			*Michalak* (2000)
	4.39 ± 0.04	87.3			*Hilton* (1999)
	4.70	93.5			*Standish* (1998)
	4.759 ± 0.023	94.7			*Viateau and Rapaport* (1998)
	5.0 ± 0.2	99			*Viateau and Rapaport* (1995)
		103			*Hilton et al.* (1996)
	4.74 ± 0.3	94			*Goffin* (1991)
	5.0 ± 0.2	99			*Standish and Hellings* (1989)
	5.21 ± 0.3	103			*Landgraf* (1988)
	5.9 ± 0.3	117			*Schubart and Matson* (1979)
			848.4 ± 19.7		*Tedesco et al.* (1992)
			941.4 ± 34		*Millis et al.* (1987)
2 Pallas (B)	1.078 ± 0.038	21.4	532.6 ± 6	2.71 ± 0.11	*Standish* (2001), *Dunham et al.* (1990)
	1.17 ± 0.03	23.3			*Goffin* (2001)
	1.21 ± 0.26	24.1			*Michalak* (2000)
	1.59 ± 0.05	31.6			*Hilton* (1999)
	1.00	21.4			*Standish* (1998)
	1.4 ± 0.2	28			*Standish and Hellings* (1989)
	1.08 ± 0.22	21	538		*Schubart and Matson* (1979)
			498.1 ± 18.8		*Tedesco et al.* (1992)
			538 ± 12		*Wasserman et al.* (1979)
			524.4 ± 15.2		*Drummond and Cocke* (1989)
4 Vesta (V)	1.341 ± 0.015	26.7	529 ± 10	3.44 ± 0.12	*Standish* (2001), *Thomas et al.* (1997)
	1.36 ± 0.05	27.0			*Michalak* (2000)
	1.69 ± 0.11	34			*Hilton* (1999)
	1.30	25.9			*Standish* (1998)
	1.33	26			*Goffin* (1991)
	1.5 ± 0.3	30			*Standish and Hellings* (1989)
	1.38 ± 0.12	27	525		*Schubart and Matson* (1979)
	1.17 ± 0.10	23			*Hertz* (1966)
			468.3 ± 26.7		*Tedesco et al.* (1992)
10 Hygeia (C)	0.49 ± 0.21	10	407.1 ± 6.8	2.76 ± 1.2	*Goffin* (1991), *Tedesco et al.* (1992)
	0.47 ± 0.23	9			*Scholl et al.* (1987)
11 Parthenope (S)	0.0258 ± 0.001	0.513	153.3 ± 3.1	2.72 ± 0.12	*Viateau and Rapaport* (1997), *Tedesco et al.* (1992)
15 Eunomia (S)	0.042 ± 0.011	0.84	255.3 ± 15.0	0.96 ± 0.3	*Hilton* (1997), *Tedesco et al.* (1992)
16 Psyche (M)	0.087 ± 0.026	1.73	253.2 ± 4.0	2.0 ± 0.6	*Viateau* (2000), *Tedesco et al.* (1992)
20 Massalia (S)	0.0264 ± 0.0041	0.525	145.5 ± 9.3	3.26 ± 0.6	*Bange* (1998), *Tedesco et al.* (1992)
22 Kalliope (M)				2.5 ± 0.3	*Margot and Brown* (2001)
24 Themis (C)	0.289 ± 0.126	5.75			*Lopez Garcia et al.* (1997)
45 Eugenia (F)	0.030	0.60	214.6 ± 4.2	$1.2^{+0.6}_{-0.2}$	*Merline et al.* (1999)
87 Sylvia (P)	0.076	1.51 ± 0.15	260.94 ± 13.3	1.62 ± 0.3	J.-L. Margot (personal communication, 2001), *Tedesco et al.* (1992)
90 Antiope (C)			120.07 ± 4.0	1.3	*Weidenshilling et al.* (2001), *Tedesco et al.* (1992)
121 Hermione (C)	0.047 ± 0.008	0.93	209.0 ± 4.7	1.96 ± 0.34	*Viateau* (2000), *Tedesco et al.* (1992)
243 Ida (S)	0.00021	0.0042 ± 0.0006	31.4	2.6 ± 0.5	*Belton et al.* (1995)
253 Mathilde (C)	0.00052	0.0103 ± 0.0004	53.02	1.3 ± 0.2	*Yeomans et al.* (1997)
433 Eros (S)	0.0000336	0.00067 ± 0.00003	17.36 ± 1.2	2.67 ± 0.03	*Yeomans et al.* (2000)
704 Interamnia (F)	0.37 ± 0.17	7 ± 3	316.6 ± 5.2	4.4 ± 2.1	*Landgraf* (1992), *Tedesco et al.* (1992)
762 Pulcova (FC)			137.09 ± 3.2	1.8 ± 0.8	*Merline et al.* (2000), *Tedesco et al.* (1992)
804 Hispania (PC)	0.05 ± 0.04	0.995 ± 0.796	157.3 ± 5.3	4.9 ± 3.9	*Landgraf* (1992), *Tedesco et al.* (1992)
1999 KW4		$2.16 \pm 0.43 \times 10^{-7}$	1.2 ± 0.12	2.39 ± 0.9	J.-L. Margot (personal communication, 2001)
2000 DP107 (C)		$4.34^{+1.91}_{-0.56} \times 10^{-8}$	0.8 ± 0.15	$1.62^{+1.2}_{-0.9}$	J.-L. Margot (personal communication, 2001)
2000 UG11		$9.35^{+1.87}_{-3.74} \times 10^{-10}$	0.23 ± 0.03	$1.47^{+0.6}_{-1.3}$	J.-L. Margot (personal communication, 2001)

Figure 1. Mass, Diameter, and Density Measurements of Asteroids in the Asteroid Belt[13]

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[13] Source: Britt et al., “Asteroid Density, Porosity, and Structure,” 486.

Figure 2 depicts the estimated macroporosities of NEAs. Macroporosity is an important property of an object as it provides insight into the strength of its internal structure and is calculated by "subtracting the average meteorite analog microporosity from the bulk porosity of an asteroid."[14] A lower number indicates a stronger internal structure, while a higher number indicates a weaker internal structure due to a higher preponderance of empty volume. Bulk porosity is "the meteorite's fractures, voids, and pores on the scale of tens of micrometers."[15] Microporosity "can represent both voids and pores that have survived from the earliest formation of these aggregates as well as post-lithification impact-induced fractures."[16]

NEAs can be delineated into three groups with regards to porosity: <10% (first group), >10% and <25% (second group), and >30%. Ceres, Vesta, and Pallas, the three most massive objects in the asteroid belt, have the lowest estimated macroporosities at <10%. This suggests that low porosity is rare, especially in larger asteroids. The asteroids in the second group, with macroporosity between 15% and 25%, were likely "extensively fractured" but still contain "some measure of coherent strength."[17] The third group's macroporosity above 30% typically "indicate [s] loose rubble or soils" on the surface of the asteroid and "more empty space than solid material" within the NEA.[18] Figure 2 illustrates that the majority of observed asteroids are between 10% and 80% porous and indicates that most asteroids contain significant porosity.

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[14] Britt et al., 492.

[15] Britt et al., 485.

[16] Britt et al., 485.

[17] Vasile and Minisci, *Asteroid and Space Debris Manipulation*, 492.

[18] Britt et al., "Asteroid Density, Porosity, and Structure," 492.

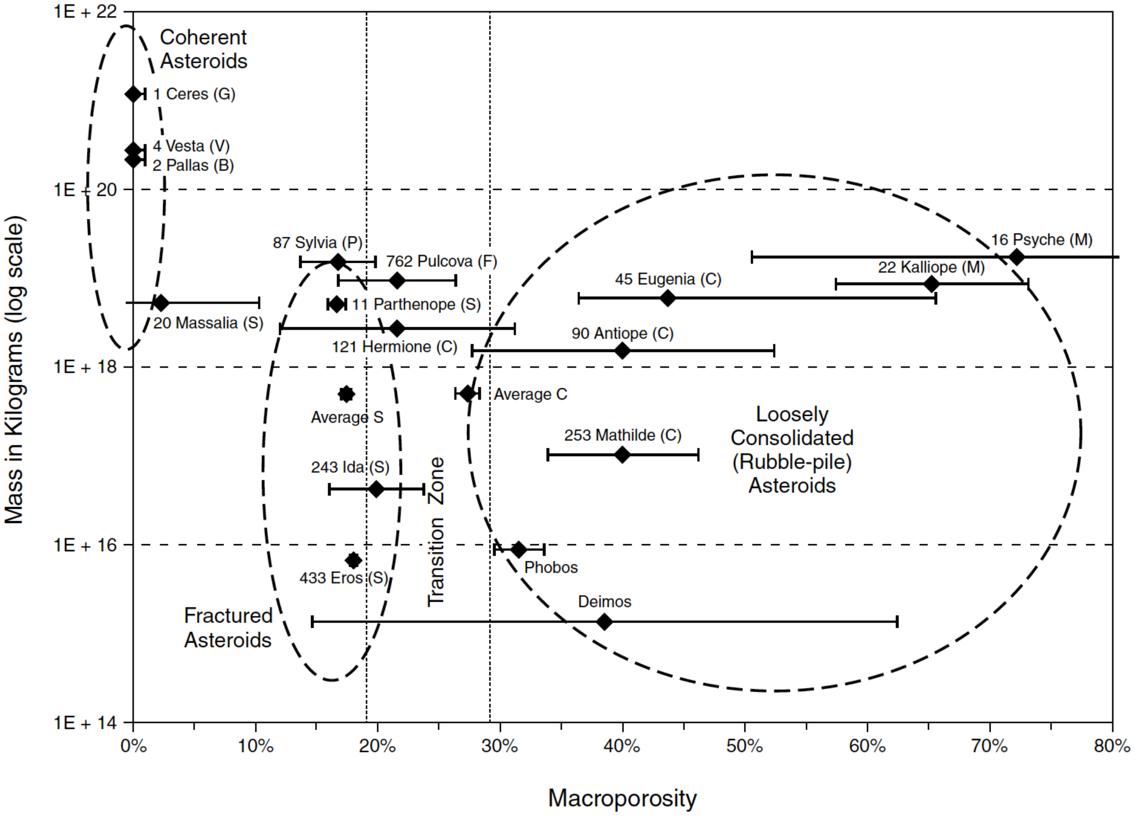

Figure 2. Estimated Macroporosity of NEAs19

2. Size Distribution of NEAs

NEAs display interesting size properties, discovered through observation. Using a statistic tool, the overall distribution of the size of NEAs can be displayed graphically and appears to follow a power-law function, which can be seen in Figure 3.[20]

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[19] Source: Britt et al., 493.

[20] Vasile and Minisci, *Asteroid and Space Debris Manipulation*, 85.

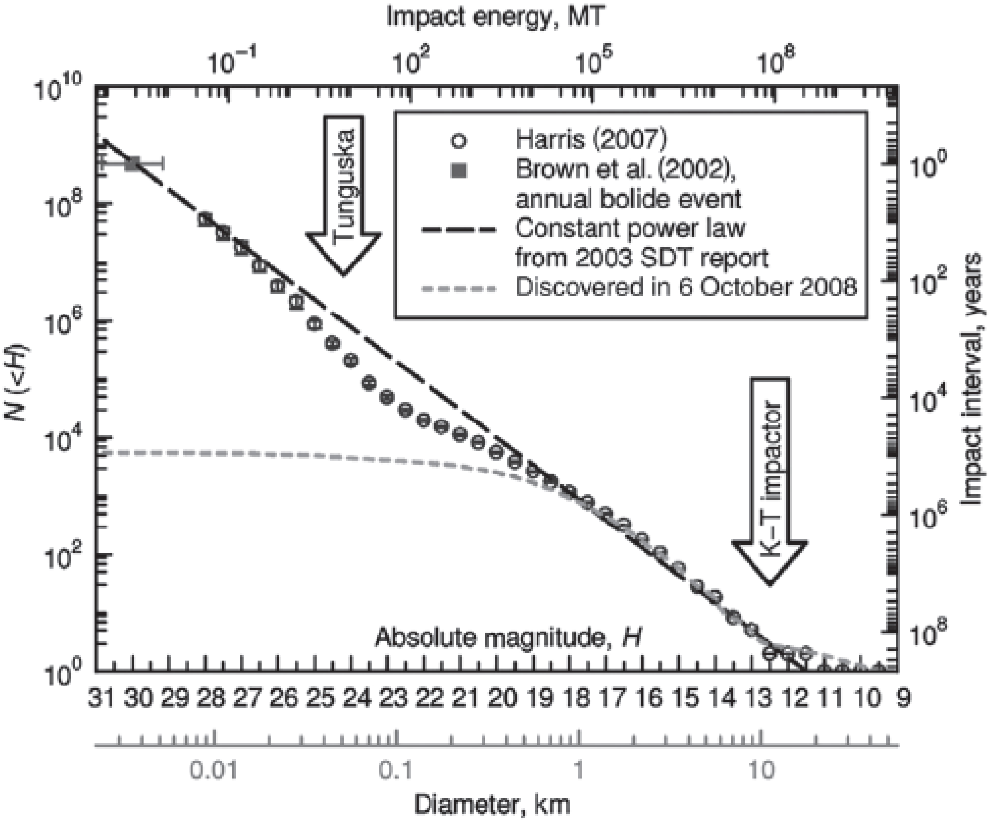

Figure 3. Size Distribution of NEAs.21

Amplifying details regarding the symbols and nomenclature in Figure 3 are provided:

> Open black circles represent the cumulative number of NEAs brighter than a given absolute magnitude H, defined as the visual magnitude V that an asteroid would have in the sky if observed at 1 AU distance from both the Earth and the Sun, at zero-phase angle. A power-law function (dashed black line) is shown for comparison. Ancillary scales give impact interval (right), impact energy in megatons TNT for the mean impact velocity 20 km/s (top), and the estimated diameter corresponding to the absolute magnitude H.[22]

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[21] Vasile and Minisci, 86.

[22] Vasile and Minisci, 86.

The phase angle is the angle created from the Sun to the asteroid to Earth, as observed from the asteroid. An asteroid would have a maximum brightness at zero-phase angle similar to how the Moon is at its brightest at zero-phase angle.

3. Spin Rates of NEAs

Determining the spin rate of NEAs is critical to asteroid sample return missions as it affects the how the spacecraft approaches and makes contact with the asteroid. The method to determine the spin rate of an asteroid is explained below:

> To determine the spin rate of an asteroid, the lightcurve is obtained, where the reflected light is plotted against time. If the asteroid has an irregular shape, which is true in most of the cases, the density of the reflected light is not constant, because as the asteroid spins a different side is facing the observer. The irregularity of the shape means that different sides of the asteroid have a different area and/or different surface structure, thus leading to the differences in the reflected light. If such a lightcurve has a periodicity in its shape, the only reasonable conclusion is that this periodicity is caused by the spin of the asteroid, a spin with the same period as the lightcurve reveals.[23]

The spin rate versus size of approximately 1,500 asteroids is shown in Figure 4.

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[23] Vasile and Minisci, 86.

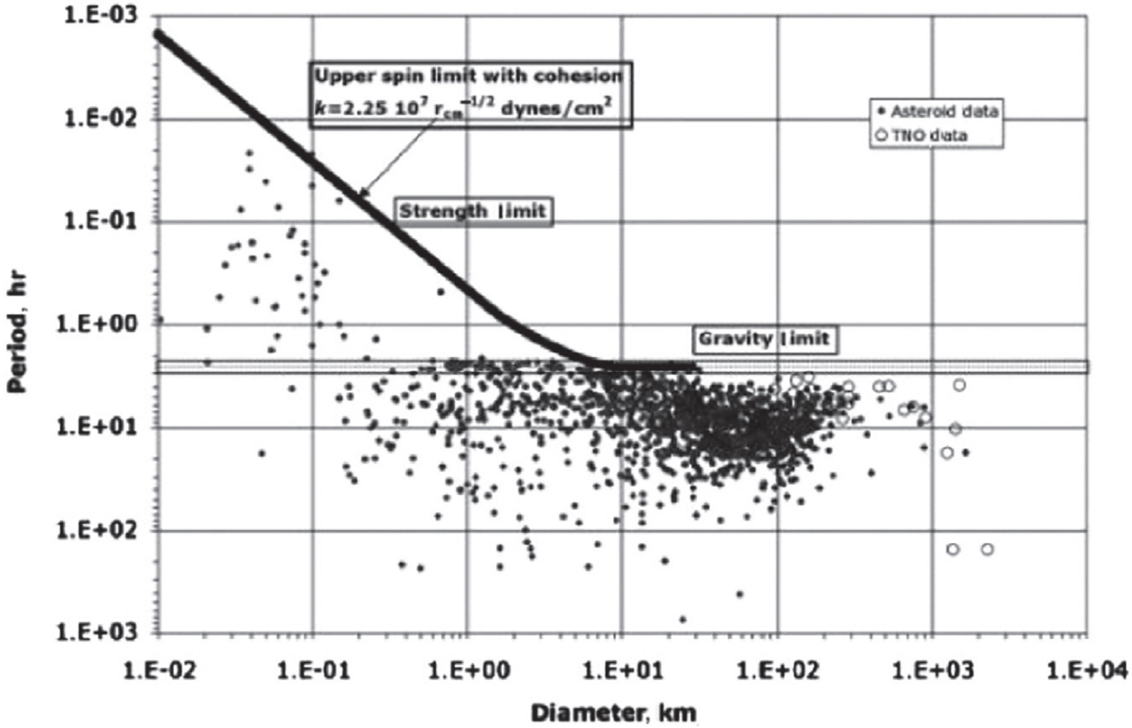

Figure 4. Spin Rates of Approximately 1,500 NEAs[24]

Amplifying details regarding the data in Figure 4 are provided below:

> The dark-sloped line assumes a size-dependent strength; it joins the horizontal grey band for materials without cohesion. On the left, the spin limit is determined by the cohesive/tensile strength of the bodies and defines a strength regime. The horizontal asymptote on the right characterizes a gravity regime where tensile/cohesive strength is of no consequence. These gravity regime values actually depend on the shape and friction angle of the material composing those bodies, so average values have been assumed. The data in the upper-left triangular region are for the fast-spinning NEAs. The triangular points for the large-diameter bodies on the right are trans-neptunian objects.[25]

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[24] Source: Vasile and Minisci, 87.

[25] Vasile and Minisci, 87.

4. Available Resources

a. Platinum Group Metals

Asteroids have a diverse set of resources that can be extracted through an asteroid mining mission. Platinum Group Metals (PGM) exist in relatively larger quantities on M-type asteroids and potentially provide enormous economic incentives for government and commercial enterprises to undertake asteroid mining missions.[26] PGM includes metallic elements such as platinum (Pt), palladium (Pd), rhodium (Rh), ruthenium (Ru), iridium (Ir), and osmium (Os).[27] Possible uses for platinum on Earth include construction, precious metals industry, and semiconductors.[28] Estimated concentrations in samples of chondrites, the "most common type of stony meteorite [which] accounts for roughly 86% of all meteorite falls," are illustrated in Figure 5.[29] Chondrites are divided into three groups: carbonaceous, ordinary, and enstatite. Carbonaceous chondrites "may contain up to 20% water by weight, as well as substantial amounts of carbon and oxidized elements."[30] Enstatite chondrites primarily contain "iron in its metallic or sulfide state."[31] Ordinary chondrites primarily "contain oxidized and volatile elements…to a lesser degree than the carbonaceous chondrites."[32] Accurate identification of platinum in chondrite samples is critical as it can help "provide diagnostic 'fingerprints' of chondrite types."[33] Developing this capability could bolster the characterization phase of NEAs for future asteroid mining missions.

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[26] J. P. Sanchez and C. McInnes, "Asteroid Resource Map for Near-Earth Space," *Journal of Spacecraft and Rockets* 48, no. 1 (January 2011): 64, https://doi.org/10.2514/1.49851.

[27] Gerlach, "Profitably Exploiting Near-Earth Object Resources," 9.

[28] Shane D. Ross, *Near-Earth Asteroid Mining* (Pasadena, California: Caltech, 2001), 4, https://www.researchgate.net/publication/228362371_Near-Earth_Asteroid_Mining.

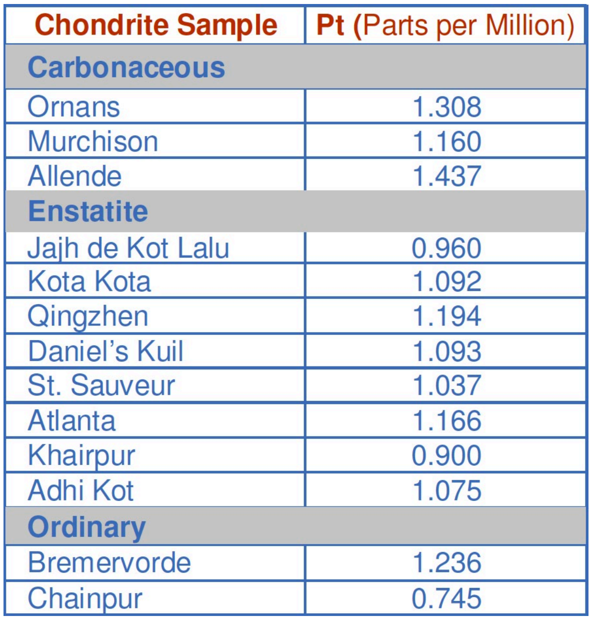
[29] "Chondrite," in *COSMOS - The SAO Encyclopedia of Astronomy*, accessed February 19, 2021, https://astronomy.swin.edu.au/cosmos/c/chondrite.

[30] COSMOS - The SAO Encyclopedia of Astronomy.

[31] M. F. Horan, R. J. Walker, and J. W. Morgan, "High Precision Measurement of Pt and Os in Chondrites," *Lunar and Planetary Science XXX*, March 15, 1999.

[32] COSMOS - The SAO Encyclopedia of Astronomy, "Chondrite."

[33] Horan, Walker, and Morgan, "High Precision Measurement of Pt and Os in Chondrites."



Chondrite Sample	Pt (Parts per Million)
Carbonaceous	
Ornans	1.308
Murchison	1.160
Allende	1.437
Enstatite	
Jajh de Kot Lalu	0.960
Kota Kota	1.092
Qingzhen	1.194
Daniel's Kuil	1.093
St. Sauveur	1.037
Atlanta	1.166
Khairpur	0.900
Adhi Kot	1.075
Ordinary	
Bremervorde	1.236
Chainpur	0.745

Figure 5. Platinum Concentration of Selected Chondrite Meteorite Samples34

b. Water

Water is arguably one of the most critical resources that could potentially be extracted from NEOs, specifically C-type asteroids. Possible uses for water during space travel include life support, propellant, agriculture, oxidizer, refrigerant, metallurgy, and radiation shielding.[35] Water can be most easily extracted from NEAs with the highest water content. Of the three main types of asteroids, C-type asteroids are believed to contain the largest percentage of water at approximately 12% and 5.7% for C1-type and C2-type asteroids, respectively.[36] In comparison, S-type asteroids contain approximately 0.15% and M-type are believed to contain insignificant amounts of water.[37]

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[34] Source: Horan, Walker, and Morgan.

[35] Ross, *Near-Earth Asteroid Mining*, 4.

[36] Brian O'Leary et al., "Retrieval of Asteroidal Materials," Research Gate, February 1979, 179, https://www.researchgate.net/publication/228362371_Near-Earth_Asteroid_Mining/link/00b7d5239743526bff000000/download.

[37] Gerlach, "Profitably Exploiting Near-Earth Object Resources," 8.

5. The Moon

A review of potential resources on NEAs must also include an examination of the viability of utilizing the Moon to enhance spacefaring capabilities within and beyond cislunar space. For instance, an architecture can focus on identifying water availability and converting that into propellant, a critical resource for an asteroid mining mission.[38] Not needing to launch a spacecraft with all of the propellant required for its mission would drastically reduce the cost of launching that spacecraft out of Earth's gravity well. Having the capability to refuel a spacecraft on the Moon would contribute to that objective. Future asteroid mining missions would benefit greatly from having this capability to refuel a spacecraft from a lunar base.

The Moon "is not a uniform, homogeneous planet…[and] consists of different rocks, formed in different ways at different times."[39] Due to the various types of lunar rocks, it is important to separate them into distinct groups. The four major groups of lunar rocks are:

> (1) *basaltic volcanic rocks*, including *lava flows* and *pyroclastic* (volcanic ash) rocks(2) *pristine* rocks from the lunar highlands (i.e., those highland rocks, shattered by impact or not, that have original lunar compositions uncontaminated by impact mixing); (3) complex *polymict breccias*, formed by impacts that shatter, mix, and recompact the lunar surface, and *impact melts* formed by melting of older lunar rocks during meteoroid impacts; and (4) the *lunar soil*, which is the fragmental (<1 cm) unconsolidated debris within the *lunar regolith* that covers the lunar surface.[40]

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[38] Paul D. Spudis and Anthony R. Lavoie, "Using the Resources of the Moon to Create a Permanent, Cislunar Space Fairing System," in *AIAA SPACE 2011 Conference & Exposition* (AIAA SPACE 2011 Conference & Exposition, Long Beach, California: American Institute of Aeronautics and Astronautics, 2011), 3, https://doi.org/10.2514/6.2011-7185.

[39] G. Jeffrey Taylor et al., "Lunar Rocks," in *Lunar Sourcebook: A User's Guide to the Moon* (Cambridge, England: Cambridge University Press, 1991), 183.

[40] Taylor et al., 184.

D. LITERATURE REVIEW

1. Technical Feasibility

The literature suggests that asteroid mining is not a technical issue, but rather an overall cost and profitability issue. Nations have the ability to identify, characterize, acquire, stow, and safely return a sample of surface regolith back to Earth. The literature agrees that there are no major impediments in the technical feasibility of an asteroid return mission, where the asteroid would be identified, characterized, captured, and returned to cislunar space or the ISS. The disagreements in the literature are primarily about what key developments are required to enable a sustainable asteroid mining architecture.

The first ever asteroid sample return capability was demonstrated on 19 November 2005 when the Japan Aerospace Exploration Agency's (JAXA) *Hayabusa 1* spacecraft collected surface material from the surface of the S-type asteroid (25143) Itokawa.[41] This was a momentous achievement as this sample return mission successfully demonstrated the capability to touchdown and collect samples from the surface of an asteroid. The sample was successfully returned back to Earth on June 13, 2010, demonstrating Japan's ability to acquire, stow, and safely return a sample of an NEA's surface.[42]

The first U.S. asteroid sample return mission commenced when NASA's *OSIRIS-REx* spacecraft launched on September 8, 2016. In October 2020, the *OSIRIS-REx* spacecraft successfully touched down and captured a sample of B-type asteroid (101955) Bennu. A B-type of asteroid is a rare type of asteroid that is mainly comprised of carbon and water-bearing minerals.[43] On May 10, 2021, *OSIRIS-REx* departed from Bennu and began its two-year trek back to Earth with a sample of its surface. The key development that enabled the successful retrieval and safe stowage of samples of the surface of Bennu is the Touch-and-Go Sample Acquisition Mechanism (TAGSAM). Upon touchdown on the asteroid, the TAGSAM uses nitrogen gas to move the surface regolith into the

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[41] Viorel Badescu, ed., *Asteroids: Prospective Energy and Material Resources* (Berlin, Heidelberg: Springer-Verlag Berlin Heidelberg, 2013), 13, https://doi.org/10.1007/978-3-642-39244-3.

[42] Badescu, 14.

[43] "Bennu," *OSIRIS-REx Mission* (blog), accessed June 1, 2021, https://www.asteroidmission.org/objectives/bennu/.

collection chamber.[44] It is scheduled to depart 101955 Bennu in May 2021 and, upon successful delivery of the sample to NASA, will mark the first successful U.S. asteroid sample return mission.[45]

Another type of an asteroid mining mission is an asteroid retrieval mission, where a spacecraft would capture and return an NEA back to cislunar space or the ISS. The "Asteroid Retrieval Feasibility Study" is one of the landmark studies regarding the technical viability of an asteroid retrieval mission. The Keck Institute for Space Studies (KISS), based out of Pasadena, CA, is a joint organization between the California Institute of Technology (Caltech) and the Jet Propulsion Laboratory (JPL). It is a privately funded think tank that studies and develops revolutionary new approaches to space missions, concepts, and technologies. Conducted by 34 authors and study participants from NASA centers, universities (Caltech, Carnegie Mellon, Harvard, Naval Postgraduate School, UCLA, UCSC, and USC), and private institutions (Arkyd Astronautics, Inc., The Planetary Society, B612 Foundation, and Florida Institute for Human and Machine Cognition), the KISS study concluded in 2012 that it appears technically feasible to characterize, capture, and return a 7-m diameter ~500,000-kg NEA to high lunar orbit by 2025.[46] While not specifically asteroid mining, capturing and returning a 550-ton asteroid would directly contribute to asteroid mining architectures that involve returning an asteroid back to cislunar space to mine. Key developments that enabled this feasibility included the ability to discover and characterize an adequate sample size of NEAs for the Asteroid Capture and Return (ACR) mission and newly developed solar electric propulsion systems that provided sufficient power to transport and return the captured asteroid.[47]

The Asteroid Return Mission Feasibility Study, conducted in 2011 by Brophy et al., concluded that there were no major obstacles to an asteroid return mission that

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[44] OSIRIS-REx Team et al., "The OSIRIS-REx Spacecraft and the Touch-and-Go Sample Acquisition Mechanism (TAGSAM)," *Space Science Reviews* 214, no. 7 (September 20, 2018): 1, https://doi.org/10.1007/s11214-018-0521-6.

[45] "OSIRIS-REx to Fly a Farewell Tour of Bennu," *OSIRIS-REx Mission* (blog), February 8, 2021, https://www.asteroidmission.org/?latest-news=osiris-rex-to-fly-a-farewell-tour-of-bennu.

[46] Brophy et al., "Asteroid Retrieval Feasibility Study," 7.

[47] Brophy et al., 6.

identified, characterized, captured, and returned a 10,000-kg asteroid to the International Space Station (ISS).[48] One of the key proposed developments of this study involved a capture canister that would allow the spacecraft to enclose, de-spin, and return the target asteroid to the ISS, enabling further extraction and analysis of its resources.[49]

The disagreement in the literature centers on the key developments that will turn the prospect of a sustainable asteroid mining architecture into a reality. Brophy et al. proposes in their 2012 "Asteroid Retrieval Feasibility Study" that the most critical follow-on activity is an observation campaign that illuminates a sufficient amount of NEAs on which asteroid mining could be successfully and confidently performed.[50] In 2013, Cenzon and Paun in *Asteroids: Prospective Energy and Material Resources* state that the critical technologies that need to be further analyzed and developed are high efficiency propulsion, material processing, electric power generation, asteroid anchoring technology, radiation protection, and NEA guidance and navigation.[51] Ryan and Kutschera in *Asteroids: Prospective Energy and Material Resources* state that the problem is not the technical viability of asteroid mining operations, but instead, the overall cost and financial return of such operations.[52] Sonters in his 1996 thesis "The Technical and Economic Feasibility of Mining the Near-Earth Asteroids" proposes that future work should be thermogravimetric quantitative studies, development of target and mission alternatives, the analysis of mathematics of non-Hohmann transfers, and autonomous machine technologies.[53]

A gap in the literature appears to be on an agreement on the key development required to make asteroid mining a reality. This thesis attempts to reprioritize what that key development should be.

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[48] John Brophy et al., "Asteroid Return Mission Feasibility Study," in *47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit* (47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, San Diego, California: American Institute of Aeronautics and Astronautics, 2011), 1, https://doi.org/10.2514/6.2011-5665.

[49] Brophy et al., 5.

[50] Brophy et al., "Asteroid Retrieval Feasibility Study," 47.

[51] Badescu, *Asteroids: Prospective Energy and Material Resources*, 194.

[52] Badescu, 648.

[53] Mark J. Sonter, "The Technical and Economic Feasibility of Mining the Near-Earth Asteroids" (University of Wollongong, 1996), 159, https://linkinghub.elsevier.com/retrieve/pii/S0094576598000873.

2. Economic Feasibility

The majority of the literature suggests that asteroid mining is not currently economically viable and that further work is required to make asteroid mining profitable and to attract additional research, development, and funding from the government, institutional, and private investors. The divergence in the literature is also on the key developments that would enable asteroid mining to be more financially profitable to attract additional funding.

Charles L. Gerlach's 2005 conference paper, "Profitably Exploiting Near-Earth Object Resources," concludes that mining NEAs are "close" to being technically and economically feasible and that further work is required.[54]

In 2019, Hein et al. proposes in their journal article "A Techno-Economic Analysis of Asteroid Mining" several key technologies that require further research and development to improve the prospect of profitability of an asteroid mining mission. They concluded that the most effective way to increase the economic viability of asteroid mining was to improve the throughput rate of the mining process (which could be technically challenging), the number of spacecraft available to conduct the mission, and the rate at which subsequent missions can be conducted.[55] Hein et al. conclude that an economically sustainable asteroid mining architecture for returning platinum does not appear financially viable.

In the "Asteroid Mining with Small Spacecraft and its Economic Feasibility" study, conducted in 2019 by Calla et al., one of the main conclusions presented was that operation of two hundred small spacecraft for approximately ten years was required to reach the financial break-even point for an asteroid mining architecture.[56] This architecture of two hundred small spacecraft would require an up-front cost of approximately $7 billion.[57]

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[54] Gerlach, "Profitably Exploiting Near-Earth Object Resources," 49.

[55] Andreas M. Hein, Robert Matheson, and Dan Fries, "A Techno-Economic Analysis of Asteroid Mining," *Acta Astronautica* 168 (March 2020): 104, https://doi.org/10.1016/j.actaastro.2019.05.009.

[56] Pablo Calla, Dan Fries, and Chris Welch, "Asteroid Mining with Small Spacecraft and Its Economic Feasibility," *Acta Astronautica* 2 (June 24, 2019): 17.

[57] Calla, Fries, and Welch, 17.

Calla et al. propose that the four key drivers that require further research and development for a sustainably profitable asteroid mining architecture are additional spacecraft size reduction, improvement in water extraction technologies, water fuel propulsion systems, and larger monolithic mining spacecraft as part of alternative or improved asteroid capture mission concepts.[58]

The literature also suggests that creating a sustainable spacefaring transportation architecture to the Moon may not be technically available yet but has the potential to be immensely profitable. In Paul D. Spudis and Anthony R. Lavoie's 2011 American Institute of Aeronautics and Astronautics (AIAA) conference paper, "Using the Resources of the Moon to Create a Permanent, Cislunar Space Faring System," this would be accomplished by establishing an outpost on the Moon that discovers, harvests, produces and processes, stores, and disseminates water from the lunar ice deposits predominantly present at the poles.[59] Harvesting water on the Moon and turning it into propellant would drastically reduce the energy costs required to launch an entire mission's worth of propellant out of Earth's gravity well by providing a space depot for spacecraft to refuel propellant. This would reduce the need to launch everything from Earth's surface, minimizing one of the major costs of the current model of an asteroid mining mission.

Similar to the gap in the technical aspect of the literature, the gap in the economic aspect of the literature appears to be on an agreement on the key developments that will increase the economic viability of asteroid mining.

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[58] Calla, Fries, and Welch, 18.

[59] Spudis and Lavoie, "Using the Resources of the Moon to Create a Permanent, Cislunar Space Fairing System," 1.

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II. OVERVIEW OF PAST SPACE EXPLORATION MISSIONS TO SMALL BODIES

As of 2021, there have been twelve space exploration missions devoted to studying asteroids.[60] Some of these space missions were flybys en route to another space object, while other missions included orbiting the asteroid or was specifically a sample return mission.[61] The following sections present a summary of these past space exploration missions and the systems utilized to help characterize asteroids, all of which may be used for future asteroid mining missions.

A. *GALILEO* ENCOUNTERS 951 GASPRA

On October 29, 1991, the first asteroid flyby occurred when NASA's *Galileo* spacecraft, en route to its mission to explore Jupiter's satellites and atmosphere, traveled past 951 Gaspra and came within 1,600 km (1,000 miles) at a relative speed of 8 km per second.[62] *Galileo's* orbiter had an on-orbit mass of 2380 kg and was powered by Radioisotope Thermal Generators (RTG) of 570W.[63] *Galileo's* probe had on-orbit mass of 335 kg and its power system was comprised of 580 W storage batteries.[64]

This flyby occurred in the asteroid belt between Mars and Jupiter. Gaspra, an S-type asteroid, is a member of the Flora family, which are asteroids located in the "innermost

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[60] "Asteroids," NASA Space Science Data Coordinated Archive, accessed February 21, 2021, https://nssdc.gsfc.nasa.gov/planetary/planets/asteroidpage.html.

[61] Badescu, *Asteroids: Prospective Energy and Material Resources*, 2.

[62] Calvin J. Hamilton, "Gaspra: Asteroid 951," Views of the Solar System, accessed February 21, 2021, https://solarviews.com/eng/gaspra.htm; Badescu, *Asteroids: Prospective Energy and Material Resources*, 3.

[63] Dr. Edwin V. Bell II, "Galileo Project Information," NASA Space Science Data Coordinated Archive, accessed February 22, 2021, https://nssdc.gsfc.nasa.gov/planetary/galileo.html.

[64] Bell II.

region of the main asteroid belt."[65] 951 Gaspra's body has a highly irregular shape estimated to have the dimensions of 18.2x10.5x8.8 km^3.[66]

Using a Solid-State Imaging Camera (SSI) instrument, the Figure 6 is a photo of Gaspra is "a mosaic of two images taken by the *Galileo* spacecraft from a range of 5,300 kilometers (3,300 miles), some 10 minutes before closest approach on October 29, 1001."[67] The SSI camera's results were combined with the Near Infrared Mapping Spectrometer (NIMS) instrument to provide a resolution of 54 meters per pixel that illustrated "a clear correlation between color and elevation."[68]

Figure 6. Mosaic Picture of Asteroid (951) Gaspra69

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[65] David Vokrouhlický, William F. Bottke, and David Nesvorný, "Forming the Flora Family: Implications for the Near-Earth Asteroid Population and Large Terrestrial Planet Impactors," *The Astronomical Journal* 153, no. 172 (March 23, 2017): 1, https://doi.org/10.3847/1538-3881/aa64dc.

[66] Badescu, *Asteroids: Prospective Energy and Material Resources*, 3.

[67] "Highest Resolution Gaspra Mosaic," NASA Jet Propulsion Laboratory, August 13, 1996, https://www.jpl.nasa.gov/images/highest-resolution-gaspra-mosaic.

[68] Badescu, *Asteroids: Prospective Energy and Material Resources*, 3–4.

[69] Source: NASA Jet Propulsion Laboratory, "Highest Resolution Gaspra Mosaic."

B. *GALILEO* AT ASTEROID (243) IDA AND ITS MOON

On August 28, 1993, *Galileo* conducted its second flyby of another asteroid, 243 Ida, en route to conduct its scientific mission to study Jupiter.[70] Ida, an S-type asteroid belonging to the Koronis family, has dimensions of 60x25x19 km^3 along its principle axis of momentum, a mass of $100x10^{15}$ kg, a rotation period of 4.633 hours, an orbital period of 4.84 years, a semi-major axis of 2.861 AU, an orbital eccentricity of 0.0412, and an orbital inclination of 1.13 degrees.[71]

The closest point of approach occurred at 2400 km "at a relative speed of 12.4 [km per second]."[72] The same instruments during the Gaspra flyby were activated to observe Ida.[73] A significant aspect of this encounter was the "serendipitous discovery of a small round moon, named Dactyle, of approximate dimensions 1.6x1.4x1.2 km^3," depicted in Figure 7.[74] The image was captured with a green filter and has a resolution of 100 meters (330 feet) per pixel.[75]

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[70] Badescu, *Asteroids: Prospective Energy and Material Resources*, 5.

[71] Badescu, 5; Dr. David R. Williams, "Asteroid Fact Sheet," NASA Space Science Data Coordinated Archive, September 27, 2019, https://nssdc.gsfc.nasa.gov/planetary/factsheet/asteroidfact.html.

[72] Badescu, *Asteroids: Prospective Energy and Material Resources*, 5.

[73] Badescu, 5.

[74] Badescu, 6.

[75] "Asteroid Ida and Its Moon," NASA Jet Propulsion Laboratory, February 1, 1996, https://www.jpl.nasa.gov/images/asteroid-ida-and-its-moon.

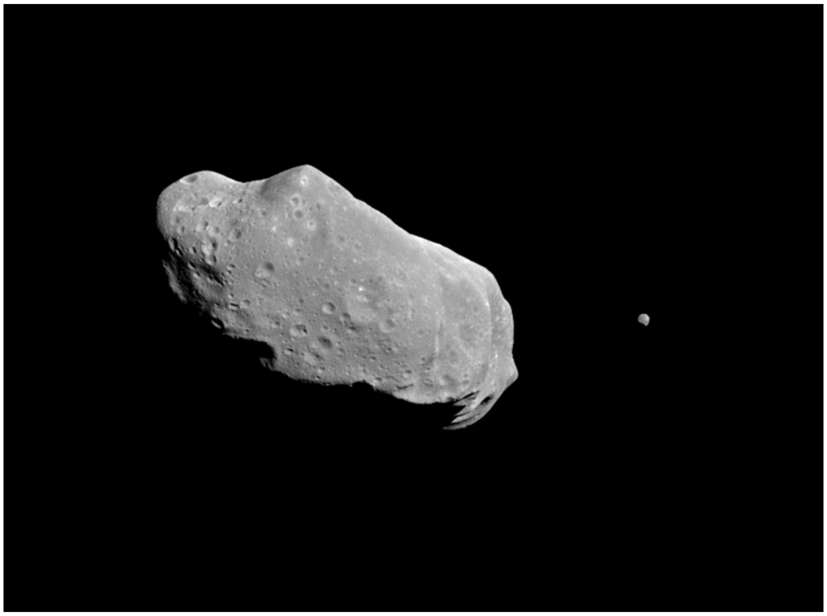

Figure 7. Asteroid (243) Ida and its Moon, Dactyl76

Other technologies that were utilized to further characterize 243 Ida were *Galileo's* onboard photometry paired with ground-based data, a combination of SSI and NIMS, and its onboard magnetometer.[77] *Galileo's* onboard photometry combined with ground-based data provided albedo data. SSI combined with NIMS yielded Ida's surface composition. The onboard magnetometer alerted *Galileo* of the existence of Ida's magnetic signature.[78]

C. NASA'S *NEAR* SPACECRAFT ENCOUNTERS 253 MATHILDE

On June 27, 1997, NASA's Near Earth Asteroid Rendezvous (*NEAR*) spacecraft, built by the Johns Hopkins University Applied Physics Laboratory (JPL), came within 1,212 kilometers of the first C-type asteroid, 253 Mathilde, in the main asteroid belt at a relative speed of 9.93 km per sec.[79] 253 Mathilde's dimensions are 66x48x46 km.[80] It has a mass 103.3×10^{15} kg, a rotation period of 417.7 hours, an orbital period of 4.31 years, a

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[76] Source: NASA Jet Propulsion Laboratory.

[77] Badescu, *Asteroids: Prospective Energy and Material Resources*, 5.

[78] Badescu, 5.

[79] Badescu, 7.

[80] Williams, "Asteroid Fact Sheet."

semi-major axis of 2.647 AU, an orbital eccentricity of 0.2655, and an orbital inclination of 6.74 degrees.[81]

NASA's *NEAR* spacecraft was launched on a Delta II launch vehicle, had a planned on-orbit mass of 805 kg, including 318 kg of propellant, and a power system of 1800 W solar panels.[82] It is equipped with "an X-ray/gamma ray spectrometer, a near-infrared imaging spectrograph, a multispectral camera fitted with a CCD imaging detector, laser altimeter, magnetometer, … four solar panels and a fixed 1.5 m X-band high-gain radio antenna."[83]

253 Mathilde was the first C-type asteroid encountered.[84] Utilizing Multispectral Imager (MSI) instrument, the *NEAR* spacecraft took an image of 253 Mathilde at a resolution of 160 meters per pixel, shown in Figure 8.[85] The image was taken from a distance of 2400 km.[86] To provide the asteroid's albedo, 0.047 at 0.55 µm, the *NEAR* spacecraft "combined disk-resolved images and ground-based low-phase angle data."[87]

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[81] Williams.

[82] Dr. David R. Williams, "NEAR Shoemaker," NASA Space Science Data Coordinated Archive, August 7, 2015, https://nssdc.gsfc.nasa.gov/planetary/near.html.

[83] Williams.

[84] Badescu, *Asteroids: Prospective Energy and Material Resources*, 7.

[85] Badescu, 7.

[86] Badescu, 7.

[87] Badescu, 8.

Figure 8. Two Separate Mosaic Images of Asteroid (253) Mathilde[88]

D. *DEEP SPACE 1* ENCOUNTERS 9969 BRAILLE

On July 29, 1999, NASA's *Deep Space 1* conducted a flyby of the Q-type NEA 9969 Braille at a relative speed of 15.5 km per second at a closest distance of 28 km.[89] A Q-type asteroid is an "uncommon inner-belt asteroid" with "absorption features shortwards and longwards of 0.7 micrometers."[90] Asteroid (9969) Braille is estimated to have dimensions of 2.1x1.0x1.0 km^3, a rotation period of 226.4 hours, an orbital period of 3.58 years, a semi-major axis of 2.341 AU, an orbital eccentricity of 0.433, and an orbital inclination of 29.00 degrees.[91]

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[88] "Two Views of Mathilde," NASA Jet Propulsion Laboratory, May 7, 2000, https://www.jpl.nasa.gov/images/two-views-of-mathilde.

[89] Badescu, *Asteroids: Prospective Energy and Material Resources*, 9.

[90] "Q-Type Asteroid," Academic Dictionaries and Encyclopedias, accessed June 1, 2021, https://en-academic.com/dic.nsf/enwiki/292492.

[91] Badescu, *Asteroids: Prospective Energy and Material Resources*, 9; Williams, "Asteroid Fact Sheet."

Deep Space 1 launched on a Delta II 7326 rocket with a mass of 373.7 kg and nominal power of 2500 W.[92] The spacecraft's launch mass was 486.3 kg.[93] It was powered by two solar panel "wings" that concentrated sunlight onto a strip of GalnP2/GaAs/Ge photovoltaic cells, and each array provided 2500 W at 100 volts at mission commencement.[94]

Deep Space 1 utilized a Miniature Integrated Camera and Imaging Spectrometer (MICAS) instrument to take "two medium-resolution images and three infrared spectra of the object from ~13,000 km."[95] Due to the larger distance at which the images were taken, the images of 9969 Braille was not as high resolution as previous missions, as illustrated in Figure 9. The left and middle images in Figure 9 were taken with the Miniature Integrated Camera Spectrometer (MICAS) 914 and 932 seconds after the encounter with 9969 Braille, and the third image on the right is a combination of those two.[96]

The most striking aspect of *Deep Space 1's* encounter with 9969 Braille occurred when its magnetometers were able to measure and determine the asteroid's magnetic fields to a resolution of 0.04 nT.[97] This was the first time that a spacecraft directly measured an asteroid's magnetic field directly.[98]

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[92] "Deep Space 1," NASA Space Science Data Coordinated Archive, accessed February 24, 2021, https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=1998-061A.

[93] NASA Space Science Data Coordinated Archive.

[94] NASA Space Science Data Coordinated Archive.

[95] Badescu, *Asteroids: Prospective Energy and Material Resources*, 9.

[96] "Composite View of Asteroid Braille from Deep Space 1," NASA Jet Propulsion Laboratory (JPL), accessed February 24, 2021, https://www.jpl.nasa.gov/images/composite-view-of-asteroid-braille-from-deep-space-1.

[97] Badescu, *Asteroids: Prospective Energy and Material Resources*, 9.

[98] Badescu, 9.

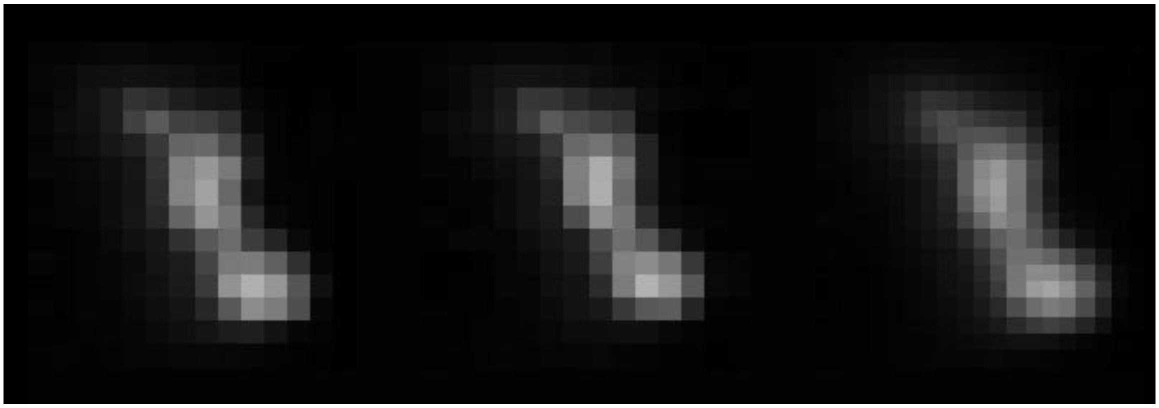

Figure 9. Composite View of 9969 Braille[99]

E. *NEAR* ORBITS ASTEROID (433) EROS

On February 14, 2000, NASA's *NEAR* spacecraft entered into an orbit around asteroid (433) Eros.[100] The S-type 433 Eros asteroid has dimensions of 34x13x13 km^3, a mass of 6.69x10^{15} kg, a rotation period of 5.27 hours, an orbital period of 1.76 years, a semi-major axis of 1.458 AU, an orbital eccentricity of 0.2227, and an orbital inclination of 10.83 degrees.[101] It has a large distinguishable crater approximately 6 km across and an albedo of 0.25 at 0.55 µm.[102]

The Magnetometer (MAG) onboard 433 Eros was able to detect the asteroid's magnetic field from greater than 100,000 km.[103] Further characterization of this asteroid was provided by the *NEAR* Infrared Spectrometer (NIS), MSI, and X-ray/Gamma-ray Spectrometer (XGRS) instruments. Confirmation of Eros' spectral ratios and the minimal presence of sulfur found on the surface were consistent with "laboratory space weathering experiment results and modeling of space weathering effects on chondritic materials," demonstrating the ability to model and predict asteroid properties form Earth.[104]

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[99] Source: NASA Jet Propulsion Laboratory (JPL), "Composite View of Asteroid Braille from Deep Space 1."

[100] Badescu, *Asteroids: Prospective Energy and Material Resources*, 10.

[101] Williams, "Asteroid Fact Sheet."

[102] Badescu, *Asteroids: Prospective Energy and Material Resources*, 11.

[103] Badescu, 11.

[104] Badescu, 11.

Figure 10 shows the northern hemisphere of Eros.

Figure 10. Mosaic of 433 Eros' Northern Hemisphere[105]

F. *STARDUST* AT ASTEROID (5535) ANNEFRANK

On November 2, 2002, NASA's *Stardust* spacecraft encountered the main belt S-type asteroid (5535) Annefrank on the way to its mission to collect the dust of comet

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[105] Source: "PIA02923: Mosaic of Eros' Northern Hemisphere," Photojournal, June 10, 2000, https://photojournal.jpl.nasa.gov/catalog/PIA02923.

81PWild2 and return it to Earth.[106] The flyby occurred at a relative speed of 7.4 km per seconds at approximately 3100 km away from the asteroid.[107] 5535 Annefrank has dimensions of 3.3x2.5x1.7 km^3, a rotation period of 15.12 hours, an orbital period of 3.29 hours, a semi-major axis of 2.213 AU, an orbital eccentricity of 0.0635, and an orbital inclination of 4.25 degrees.[108]

An instrument that contributed in characterizing 5535 Annefrank was the *Stardust* Imaging Camera.[109] The camera captured an image, shown in Figure 11, at a resolution of 185 meters per pixel.[110]

Figure 11. Image of Asteroid (5535) Annefrank111

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[106] Badescu, *Asteroids: Prospective Energy and Material Resources*, 11.

[107] Badescu, 11.

[108] Badescu, 11; Williams, “Asteroid Fact Sheet.”

[109] Badescu, *Asteroids: Prospective Energy and Material Resources*, 12.

[110] Badescu, 12.

[111] Source: “Asteroid 5535 Annefrank,” NASA Jet Propulsion Laboratory, November 26, 2003, https://stardust.jpl.nasa.gov/photo/annefrank.html.

G. ESA’S *ROSETTA* ENCOUNTERS ASTEROID (2867) STEINS

On September 5, 2008, the European Space Agency (ESA) spacecraft encountered the E-type main belt asteroid (2867) Steins en route to its mission to study the comet 67P/Churyumov-Gerasimenko.[112] An E-type asteroid is a rare asteroid with a “strong absorption feature” of 0.50 micrometers.[113] The flyby occurred at a distance of approximately 800 km at a relative speed of 8.6 km per second.[114] Steins has dimensions of 6.8x5.7x4.4 km^3, a rotation period of 6.049 hours, an orbital period of 3.64 years, a semi-major axis of 2.363 AU, an orbital eccentricity of 0.1455, and an orbital inclination of 9.93 degrees.[115] Asteroid (2867) Steins is shown in Figure 12.

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[112] Badescu, *Asteroids: Prospective Energy and Material Resources*, 15.

[113] Paul R. Weissman et al., “Rosetta Target Asteroid 2867 Steins: An Unusual E-Type Asteroid,” *Meteoritics & Planetary Science* 43, no. 5 (May 2008): 906, https://doi.org/10.1111/j.1945-5100.2008.tb01089.x.

[114] Badescu, *Asteroids: Prospective Energy and Material Resources*, 15.

[115] Williams, “Asteroid Fact Sheet.”

Figure 12. Asteroid (2867) Steins Captured by Rosetta116

Fourteen scientific instruments were used to characterize Steins during the flyby, including the Optical, Spectroscopic, and Infrared Remote Imaging System (OSIRIS), Visible and Infrared Thermal Imaging Spectrometer (VIRTIS), Microwave Instrument for the *Rosetta* Orbiter (MIRO), Ultraviolet Imaging Spectrometer (ALICE), *Rosetta* Plasma Consortium (RCP) magnetometer; and the *Rosetta* Lander Magnetometer and Plasma Monitor (ROMAP) instruments.[117] The OSIRIS was a two-camera instrument that captured approximately 60% of Steins' surface with a resolution of 80 meters per pixel, shown in Figure 12.[118] The VIRTIS allows spacecraft to map low spectral resolution (VIRTIS-M) and high spectral resolution slit spectroscopy (VIRTIS-H), enabling further

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[116] Source: ESA 2008 MPS for OSIRIS Team MPS/UPD/LAM/IAA/RSSD/INTA/UPM/DASP/IDA

[117] Badescu, *Asteroids: Prospective Energy and Material Resources*, 15–16.

[118] Badescu, 15.

IR and visible spectra characterization.[119] ALICE is the first UV spectrograph that enabled low-cost imaging designed for studying comets up close.[120] The RCP instrument allowed *Rosetta* to measure the magnetic fields of a solar wind plasma.[121] The ROMAP instrument enabled *Rosetta* to measure the magnetic field and surface plasma of comet 67P/ Churyumov-Gerasimenko.[122]

H. NASA'S *DAWN* AT ASTEROID (1) CERES AND (4) VESTA

NASA's *Dawn* set out to explore 1 Ceres in July 2011 and en route, entered into orbit around the second most massive asteroid, Vesta, on July 16, 2011.[123] 4 Vesta has dimensions of 569 x 555 x 453 km, a mass of 259,000x10^{15} kg, a rotation period of 5.342 hours, an orbital period of 3.63 years, a semi-major axis of 2.362 AU, an orbital eccentricity of 0.0889, and an orbital inclination of 7.14 degrees.[124] An image of 4 Vesta is shown in Figure 13.

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[119] G. Piccioni et al., "VIRTIS: The Visible and Infrared Thermal Imaging Spectrometer" SP-1295 (2007): 1–27.

[120] S. A. Stern et al., "ALICE: The Rosetta Ultraviolet Imaging Spectrograph," *Space Science Reviews* 128, no. 1–4 (February 2007): 1, https://doi.org/10.1007/s11214-006-9035-8.

[121] Karl-Heinz Glassmeier et al., "RPC-MAG: The Fluxgate Magnetometer in the ROSETTA Plasma Consortium," *Space Science Reviews* 128, no. 1–4 (May 28, 2007): 649, https://doi.org/10.1007/s11214-006-9114-x.

[122] H. U. Auster et al., "ROMAP: Rosetta Magnetometer and Plasma Monitor," *Space Science Reviews* 128, no. 1–4 (May 2007): 221, https://doi.org/10.1007/s11214-006-9033-x.

[123] Badescu, *Asteroids: Prospective Energy and Material Resources*, 18.

[124] Williams, "Asteroid Fact Sheet."

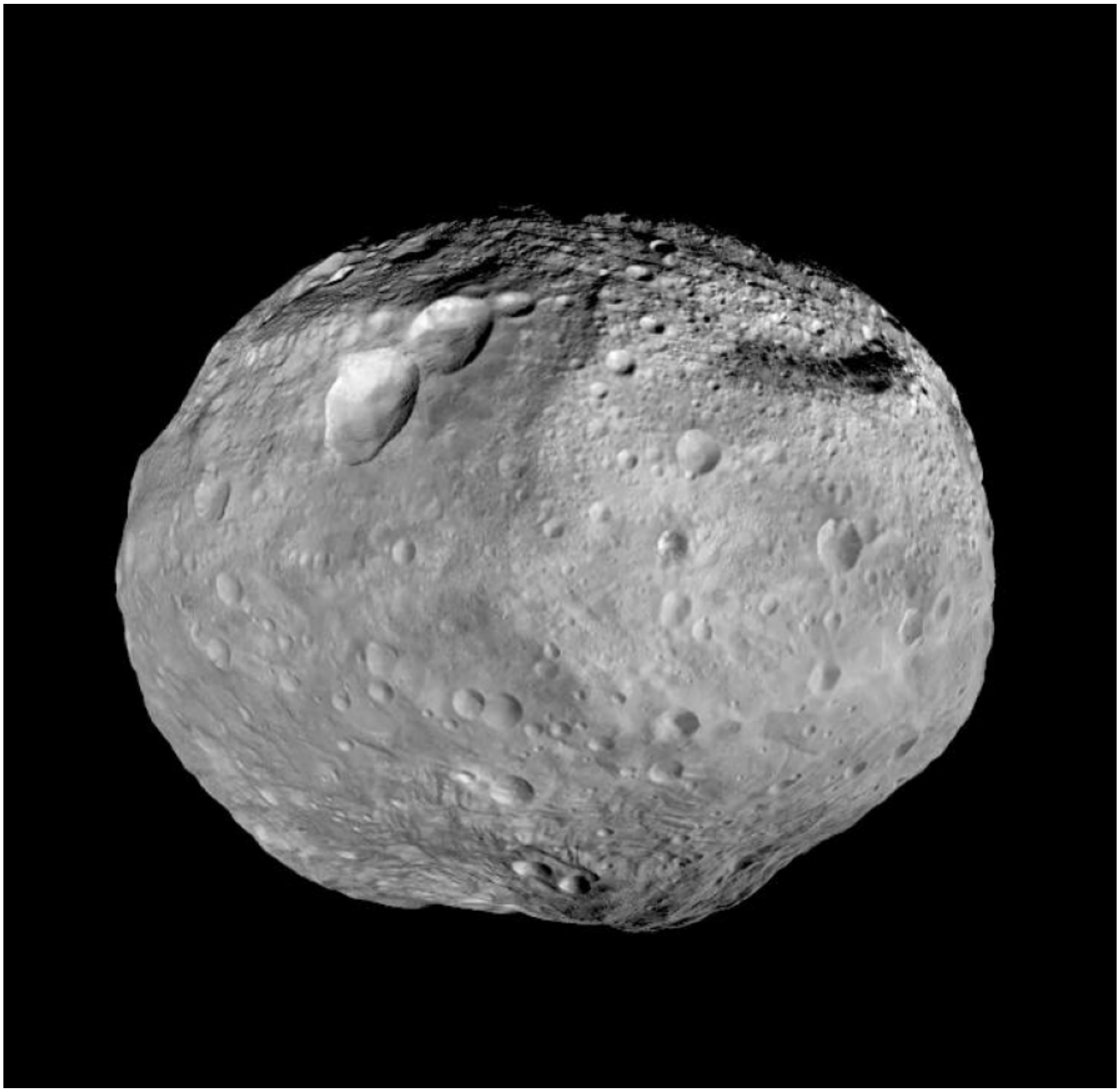

Figure 13. Image of Asteroid (4) Vesta Captured by Dawn125

NASA’s *Dawn* utilized the Framing Camera (FC) and Visible and Infrared Spectrometer (VIR) instruments to map and characterize ~80% of 4 Vesta’s surface from an altitude of ~2,700 km.[126]

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[125] Source: Badescu, *Asteroids: Prospective Energy and Material Resources*, 20.

[126] Badescu, 19.

I. CHINA'S *CHANG'E 2* AT ASTEROID (4179) TOUTATIS

China's spacecraft *Chang'e 2* encountered the S-type asteroid (4179) Toutatis at a closest distance of 770 m from its surface and a relative velocity of 10.73 km per sec.[127] 4179 Toutatis is an irregularly shaped asteroid with dimensions of 4.6x2.4x1.9 km^3, a mass of $0.05x10^{15}$ kg, a rotation period of 130. hours, an orbital period of 3.98 years, a semi-major axis of 2.534 AU, an orbital eccentricity of 0.6294, and an orbital inclination of 0.45 degrees.[128]

Extensive use of ground-based telescopes and radar facilities were utilized to characterize and observe 4179 Toutatis as it approached Earth every four years.[129] Toutatis' 3-dimensional shape was modeled using "higher resolution delay-Doppler radar observations."[130] An image of 4179 Toutatis is shown in Figure 14.

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[127] Jianghui Ji et al., "Chang'e-2 Spacecraft Observations of Asteroid 4179 Toutatis," *Proceedings of the International Astronomical Union* 10, no. S318 (2015): 1, https://doi.org/10.1017/S1743921315008674; Badescu, *Asteroids: Prospective Energy and Material Resources*, 21.

[128] Williams, "Asteroid Fact Sheet."

[129] Ji et al., "Chang'e-2 Spacecraft Observations of Asteroid 4179 Toutatis," 1.

[130] Ji et al., 1.

Figure 14. An Image of Asteroid (4179) Toutatis[131]

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[131] Source: “4179 Toutatis,” SpaceRef, 2012, http://images.spaceref.com/news/2012/ootoutatis.change.jpg.

III. TECHNOLOGICAL SURVEY OF PAST ASTEROID SAMPLE RETURN MISSIONS

A. JAXA *HAYABUSA* SPACECRAFT CONDUCTS FIRST SAMPLE RETURN MISSION AT ASTEROID (25143) ITOKAWA

On November 19 and November 25, 2006, the Japan Aerospace Exploration Agency (JAXA) *Hayabusa* spacecraft conducted two touchdowns on the S-type asteroid (25143) Itokawa in the first asteroid sample return mission in history.[132] This was the first time a spacecraft successfully landed on, obtained a sample from, and took off from an asteroid.[133] It also attempted to launch and land a microrover on the asteroid's surface; however, the landing was unsuccessful.[134] Though the mission had many technical glitches, *Hayabusa* was able to safely return an extremely small amount of surface material for analysis.[135]

JAXA's *Hayabusa* orbited Itokawa at an altitude of 7 km. Itokawa has dimensions of 0.5x0.3x0.2 km^3, a mass of 0.000035×10^{15} kg, a rotation period of 12.13 hours, an orbital period of 1.52 years, a semi-major axis of 1.324 AU, an orbital eccentricity of 0.2801, and an orbital inclination of 1.62 degrees.[136] An image ~8 km from the surface was captured in September 2005, shown in Figure 14.

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[132] Badescu, *Asteroids: Prospective Energy and Material Resources*, 13.

[133] "Hayabusa," NASA Science Solar System Exploration, January 25, 2018, https://solarsystem.nasa.gov/missions/hayabusa/in-depth.

[134] Badescu, *Asteroids: Prospective Energy and Material Resources*, 13.

[135] Elizabeth Howell, "Hayabusa: Troubled Sample-Return Mission," Space, March 31, 2018, https://www.space.com/40156-hayabusa.html.

[136] Williams, "Asteroid Fact Sheet."

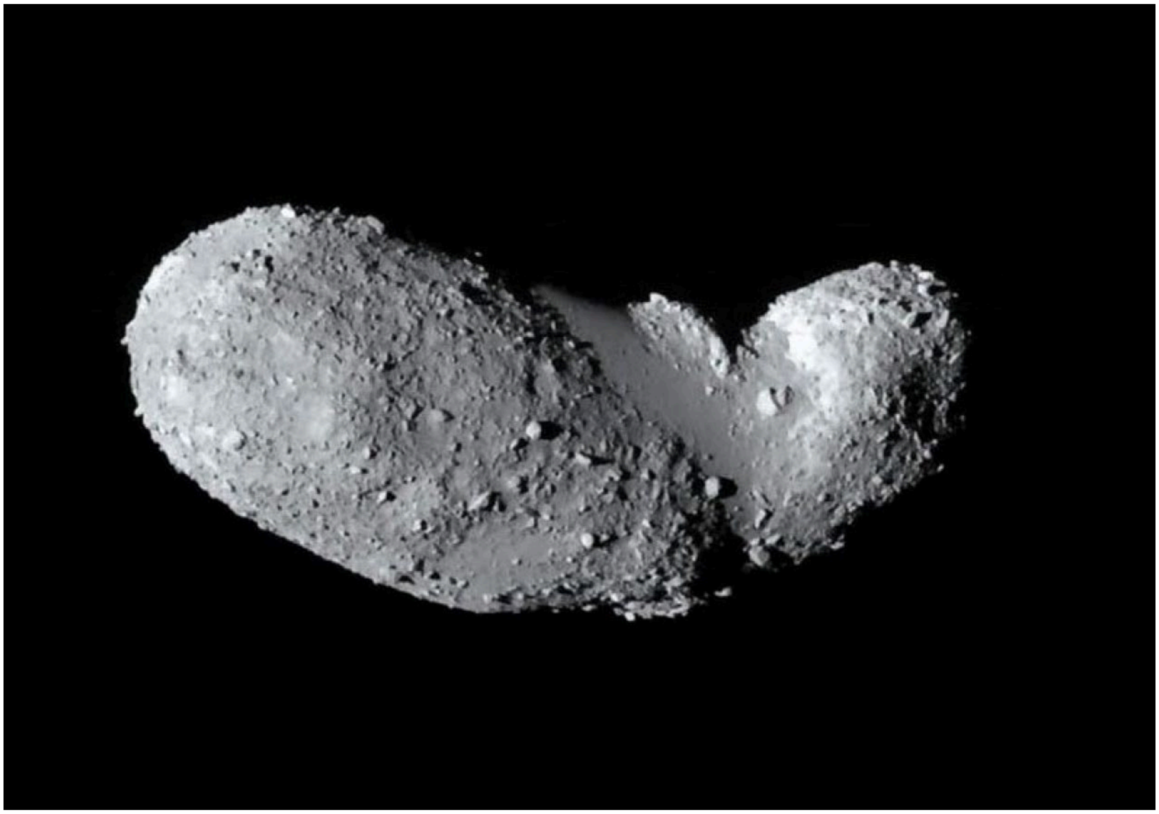

Figure 15. An image of Asteroid (25143) Itokawa Captured from the Hayabusa Spacecraft137

The *Hayabusa* mission had five main objectives, which were all accomplished:

> (1) to conduct interplanetary flight with a new ion-engine propulsion system; (2) to perform autonomous navigation by determining its own location and landing on a target using its own calculations; (3) to collect samples from an asteroid; (4) to accelerate through space using ion engines in conjunction with an Earth swing-by; and (5) to bring to Earth a capsule containing samples from an asteroid.[138]

Hayabusa had a weight of 510 kg, a hexahedron core dimensions of 1.0x1.1x1.6 m, and a 5.7 m width of the solar panel at full deployment.[139] The instruments onboard

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[137] Source: Badescu, *Asteroids: Prospective Energy and Material Resources*, 14.

[138] "Hayabusa's Return Journey to Earth: The Final Stage," JAXA, 2003, https://global.jaxa.jp/article/special/hayabusa/index_e.html.

[139] "Hayabusa," Institute of Space and Astronautical Space (ISAS), accessed April 2, 2021, https://www.isas.jaxa.jp/en/missions/spacecraft/past/hayabusa.html.

Hayabusa were Light Detection and Ranging (LIDAR), NIS, X-Ray Fluorescence Spectrometer (XRS), Wide-view Camera (ONC-W), Telescopic Camera (AMICA), target marker, sampler and reentry capsule, and a Micro/Nano Experimental Robot Vehicle for Asteroid (MINERVA).[140]

It was astounding that *Hayabusa* accomplished all of its mission objectives because of the many ways the mission went wrong. This was the first controlled landing on an asteroid and first ascent from an asteroid in the solar system.[141] A solar flare in 2003 degraded *Hayabusa's* solar panels, which reduced the efficiency of its ion engine and delayed its rendezvous with Itokawa by three months.[142] In July 2005, two of its reaction wheels failed after collecting data about the asteroid's shape, spin, composition, density, and other features.[143] The first loss of a reaction wheel occurred on July 2005 before rendezvous with Itokawa.[144] The second loss of a reaction wheel occurred on September 2005 during rendezvous.[145] Countermeasures for the first and second loss of its reaction wheels were the establishment of 3-axis attitude control by reaction wheels and the establishment of 3-axis attitude control by short pulse operation of 2-prop thrusters.[146] In late 2005, JAXA aborted a practice descent due to difficulties finding a suitable landing site.[147] It attempted to send its MINERVA rover to take pictures and samples of the surface. It never landed or returned, and it is believed that the rover drifted off into space due to technical malfunctions. *Hayabusa* also attempted to send a probe to land on the surface of Itokawa to gather asteroid dust on two separate occasions. On the first occasion,

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[140] "Hayabusa," NASA Jet Propulsion Laboratory (JPL), accessed April 2, 2021, https://www.jpl.nasa.gov/missions/hayabusa.

[141] NASA Science Solar System Exploration, "Hayabusa."

[142] Mika McKinnon, "Everything That Could Go Wrong for Hayabusa Did, and Yet It Still Succeeded," Gizmodo, October 15, 2015, https://gizmodo.com/everything-that-could-go-wrong-for-hayabusa-did-and-ye-1730940605.

[143] McKinnon.

[144] H. Kuninaka, "Lessons Learned on Hayabusa," NASA, 2010, https://www.nasa.gov/pdf/474205main_Kuninaka_HayabusaLL_ExploreNOW.pdf.

[145] Kuninaka.

[146] Kuninaka.

[147] Howell, "Hayabusa."

"an obstacle triggered an abort attempt, but it was too close and instead descended in safe mode."[148] During the second attempt, "a leak in the thruster system" resulted in the spacecraft going into safe mode again.[149] As *Hayabusa* departed Itokawa on its voyage back to Earth, the spacecraft encountered more technical glitches, such as "frozen pipes, leaking fuel, and communications glitches."[150]

Figure 16 shows *Hayabusa* casting a shadow on Itokawa.

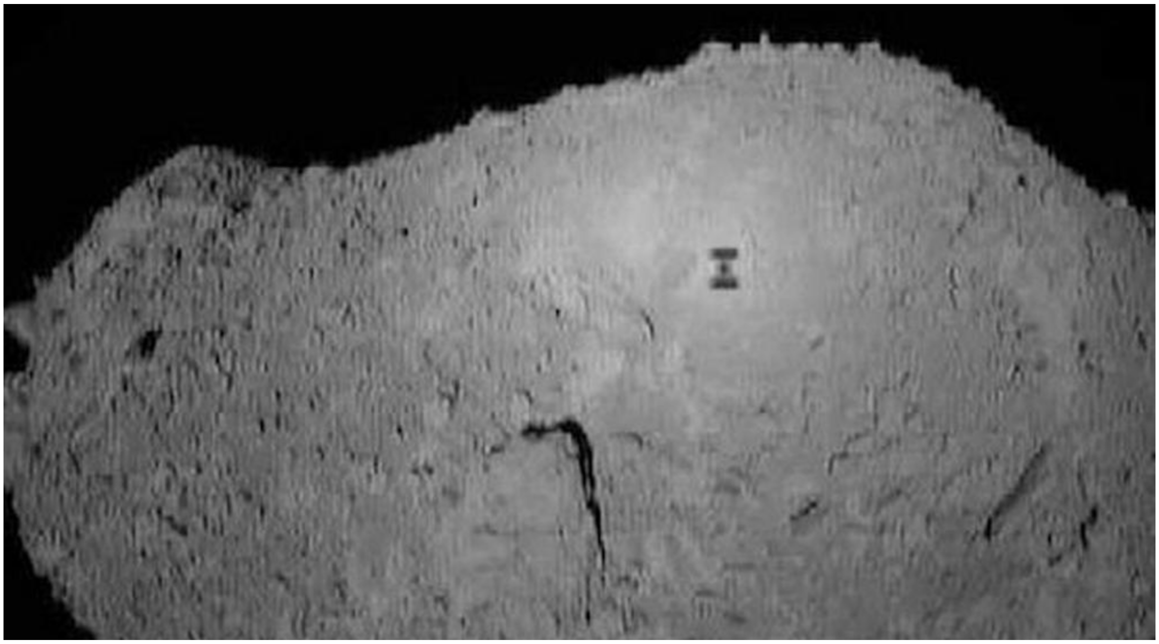

Figure 16. Image of Hayabusa Casting a Shadow on Asteroid (25143) Itokawa151

The total mass of the sample returned from 25143 Itokawa's surface is less than 1 milligram.[152] It is estimated that *Hayabusa* returned 1,500 particles, most of which were

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[148] McKinnon, "Everything That Could Go Wrong for Hayabusa Did, and Yet It Still Succeeded."

[149] McKinnon.

[150] Howell, "Hayabusa."

[151] Source: McKinnon, "Everything That Could Go Wrong for Hayabusa Did, and Yet It Still Succeeded."

[152] Emily Lakdawalla, "LPSC 2011: Analysis of the Grains Returned by Hayabusa," The Planetary Society, March 16, 2011, https://www.planetary.org/articles/2960.

10 microns wide, from 25143 Itokawa's surface.[153] "Oxygen isotope abundance measurements" and "neutron activation analysis" were used to help further characterize Itokawa's composition and history.[154]

B. *OSIRIS-REX* AT ASTEROID (101955) BENNU

On September 8, 2016, the Origins, Spectral Interpretation, Resource Identification, Security and Regolith-Explorer (*OSIRIS-REx*) spacecraft was launched from Cape Canaveral, Florida, on an Atlas V 411 rocket towards asteroid (101955) Bennu.[155] Its scientific mission objectives were to "return and analyze a sample of Bennu's surface, map the asteroid, document the sample site, measure the orbit deviation caused by non-gravitational forces (the Yarkovsky effect), [and] compare observations at the asteroid to ground-based observations."[156]

Bennu is a roughly 500 m diameter B-class NEA located approximately 200 million miles from Earth.[157] It has a mass of $0.000073 \text{x} 10^{15}$ kg, a rotation period of 4.276 hours, an orbital period of 1.20 years, a semi-major axis of 1.126 AU, an orbital eccentricity of 0.2037, and an orbital inclination of 6.03 degrees. Figure 17 depicts an image of 101955 Bennu.

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[153] Lakdawalla.

[154] "JAXA | First Analysis of Tiny Particles from Itokawa," JAXA, 2010, https://global.jaxa.jp/article/special/itokawa/bunseki_e.html; Lakdawalla, "LPSC 2011."

[155] "Mission Operations," *OSIRIS-REx Mission* (blog), accessed February 18, 2021, https://www.asteroidmission.org/objectives/mission-operations/.

[156] "The Mission," *OSIRIS-REx Mission* (blog), accessed February 18, 2021, https://www.asteroidmission.org/objectives/.

[157] C. W. Hergenrother et al., "Introduction to the Special Issue: Exploration of the Activity of Asteroid (101955) Bennu," *Journal of Geophysical Research: Planets* 125, no. 9 (September 2020): 1, https://doi.org/10.1029/2020JE006549.

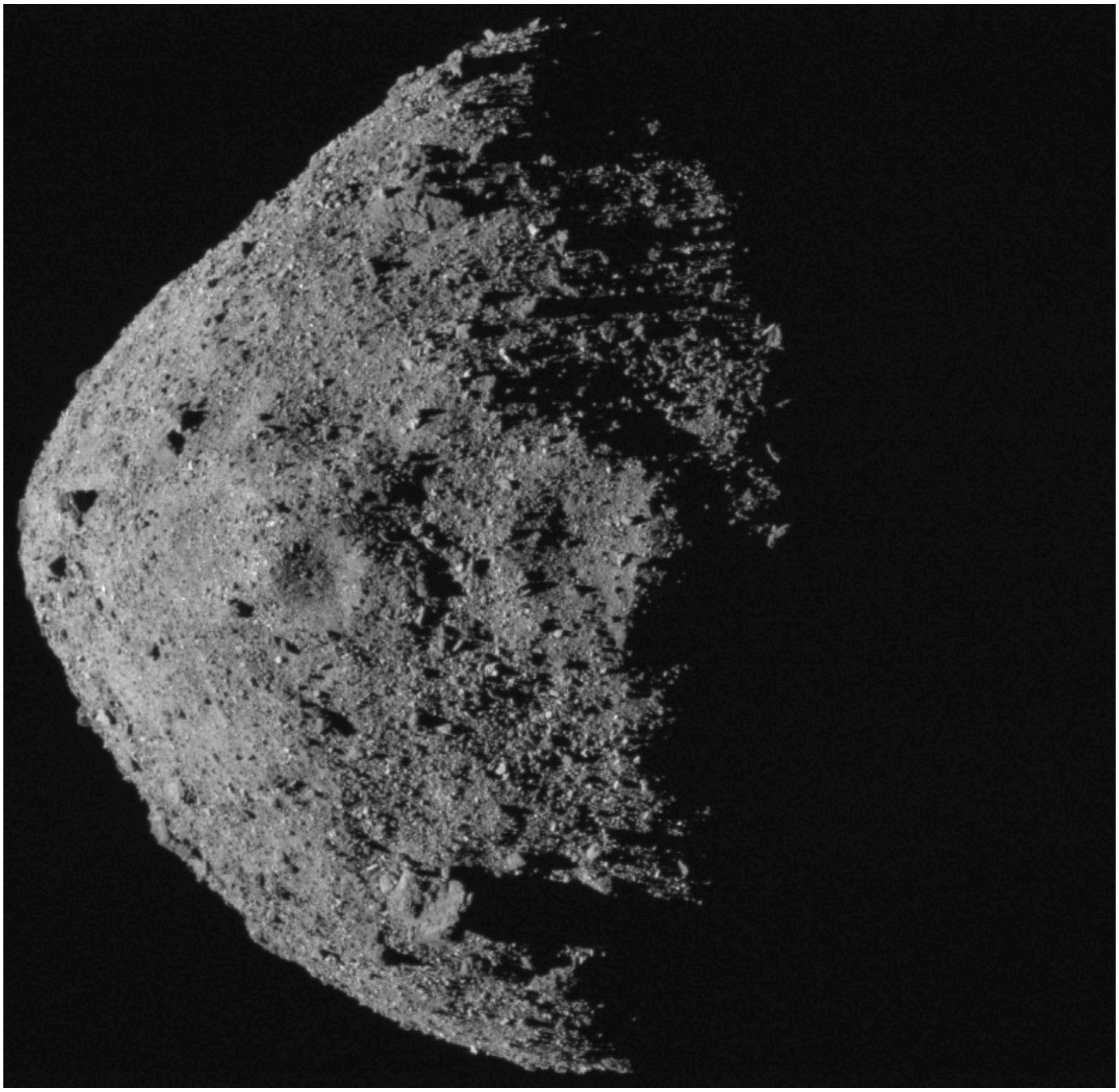

Figure 17. An Image of Asteroid (101955) Bennu158

On October 20, 2020, the *OSIRIS-REx* spacecraft successfully made contact with asteroid (101955) Bennu, "touching down within three feet of the targeted location."[159] Figure 18 depicts an image of spacecraft touchdown at sample site Nightingale on Bennu's surface.

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[158] "Bennu's Striking Craters," OSIRIS-REx: Asteroid Sample Return Mission, April 28, 2020, https://www.asteroidmission.org/wp-content/uploads/2020/05/20200428GargoyleBenben.png.

[159] Rob Garner, "OSIRIS-REx TAGs Surface of Asteroid Bennu," Text, NASA, October 21, 2020, http://www.nasa.gov/feature/goddard/2020/osiris-rex-tags-surface-of-asteroid-bennu.

Figure 18. Image of OSIRIS-REx Touchdown on Bennu's Surface at Sample Site Nightingale[160]

A key development that enabled the *OSIRIS-REx* Sample Return Mission was its Touch-and-Go Sample Acquisition Mechanism (TAGSAM). The TAGSAM is a gas-driven sample collection mechanism that enables *OSIRIS-REx* to retrieve surface samples from asteroids.[161] In addition to N_2 bottles, the TAGSAM assembly consisted of an elbow, arm, shoulder, wrist, compression section, and head, which was securely stowed in a launch container until arrival at Bennu.[162] This assembly is shown in Figure 19.

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[160] Source: "Images Before and After Spacecraft Touchdown on Bennu," OSIRIS-REx: Asteroid Sample Return Mission, October 20, 2020, https://www.asteroidmission.org/wp-content/uploads/2020/10/TAG-2-frames.gif.

[161] OSIRIS-REx Team et al., "The OSIRIS-REx Spacecraft and the Touch-and-Go Sample Acquisition Mechanism (TAGSAM)," 20.

[162] OSIRIS-REx Team et al., 21.

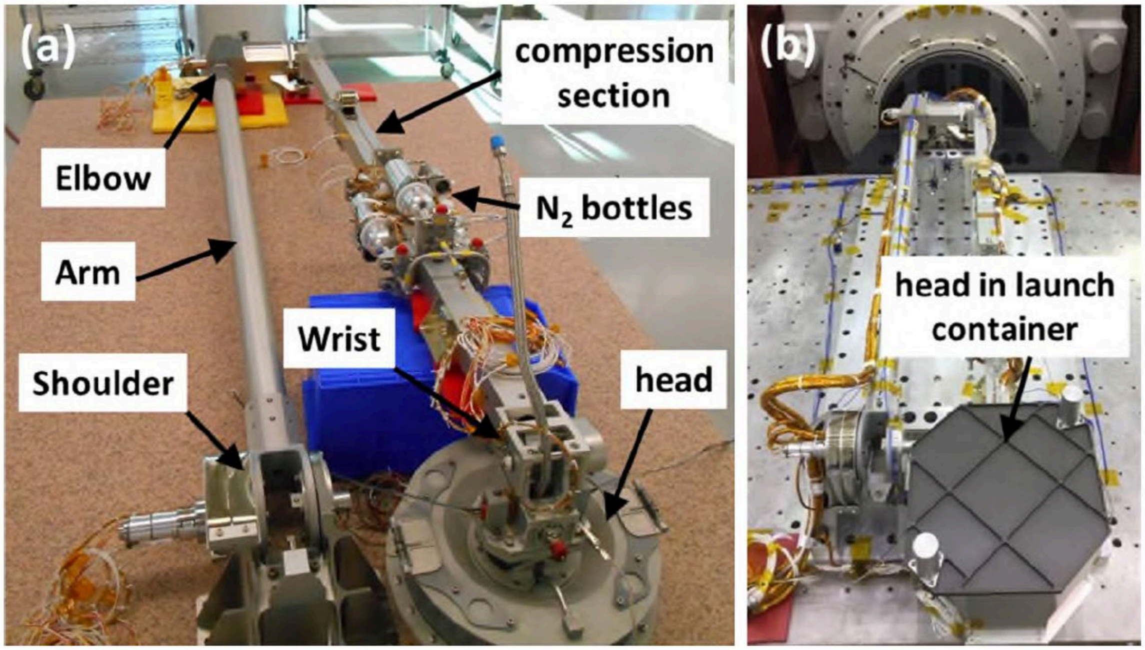

Figure 19. An Image of the TAGSAM Assembly and its Launch Container163

The process to collect a sample from Bennu is illustrated in Figure 20 and involves TAG rehearsals, the actual TAG, sample mass verification, and Sample Return Capsule (SRC) stowage.[164] The TAG rehearsals prepare *OSIRIS-REx* to proceed to the actual TAG event. These rehearsals involve executing burns and verifying the expected images, ranges, range rates, and attitude measurements.[165] During the TAG event, *OSIRIS-REx* descends onto Bennu and releases high-purity nitrogen gas, “mobilizing surface materials under the TAGSAM head where they are captured.”[166] The spacecraft then conducts two evaluations to verify the collected surface material.[167] Upon verifying the sample mass, the arm securely stows the TAGSAM head into the SRC.[168]

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[163] Source: OSIRIS-REx Team et al., 21.

[164] OSIRIS-REx Team et al., 17–19.

[165] OSIRIS-REx Team et al., 17.

[166] OSIRIS-REx Team et al., 18.

[167] OSIRIS-REx Team et al., 18.

[168] OSIRIS-REx Team et al., 19.

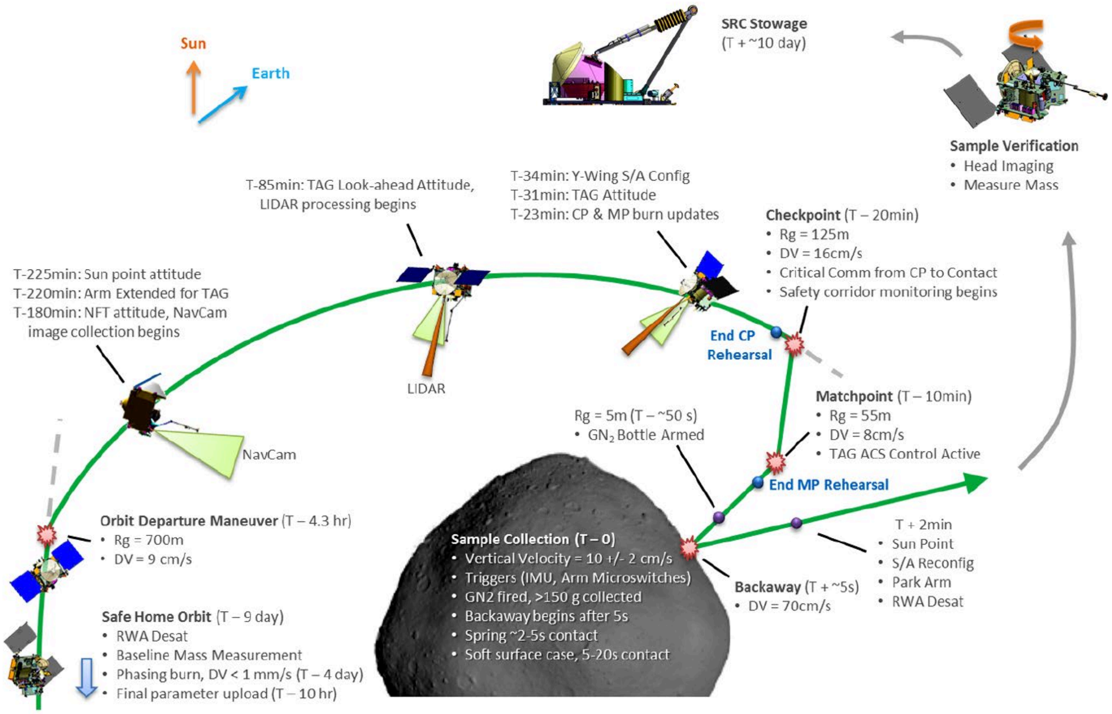

Figure 20. Overview of OSIRIS-REx Collecting a Sample Utilizing the TAGSAM[169]

There were various challenges and lessons learned from the *OSIRIS-REx* mission. One lesson learned was from the *OSIRIS-REx* Autonomous Navigation Natural Feature Tracking (NFT) flight hardware and software. NFT is an optical navigation system that compares images collected by the Navigation Camera against the predicted appearance of Bennu's surface.[170] The quality of the match in the two images (collected vs. onboard) is quantified by a correlation score and helps determine the orbital orientation of a small asteroid.[171] This process determines the orbital orientation of a small asteroid. An example of this process is shown in Figure 21.

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[169] Source: OSIRIS-REx Team et al., 17.

[170] David A Lorenz et al., "Lessons Learned from OSIRIS-REx Autonomous Navigation Using Natural Feature Tracking," 2019, 4.

[171] Lorenz et al., 4.

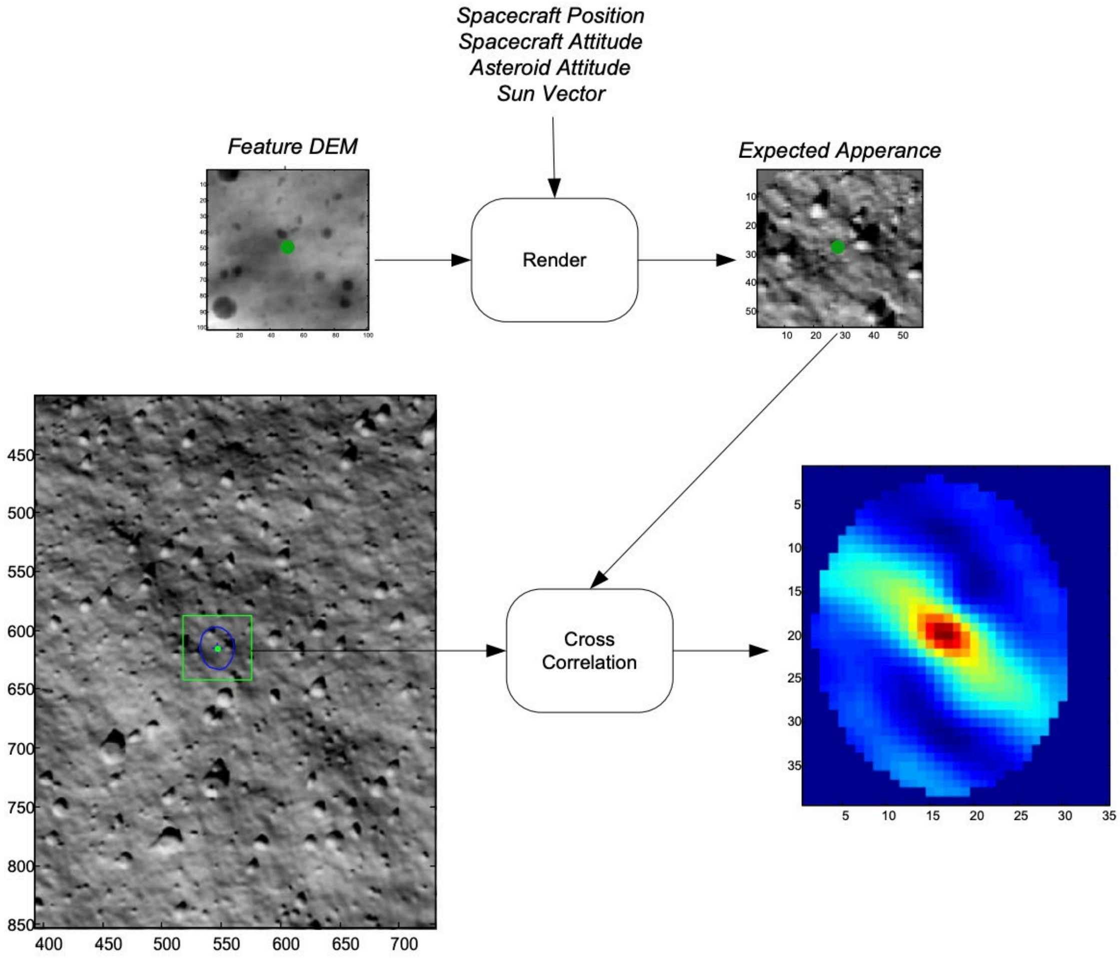

Figure 21. Example of NFT Feature Matching Process172

There were various lessons learned in *OSIRIS-REx's* NFT systems and interfaces. The details of the NFT rendering software requirements were not easily communicated which led to difficulties in establishing the correct system constraints.[173] In other words, the NFT system added complexity in constraining the system and establishing interface requirements between the NFT and Altimetry Working Group (ALTWG) teams. These difficulties were corrected when more systems team members were added to help resolve the issue. They modified the requirements to ensure the verification process was more

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[172] Source: Lorenz et al., 4.

[173] Lorenz et al., 6.

integrated between the NFT and ALTWG.[174] The advantage was that the requirements were now much simpler to interpret. The disadvantage was that this added complexity to the verification process.[175]

The backup status of NFT also created challenges due to its late addition to the *OSIRIS-REx* program. NFT was a backup system, which resulted in NFT being prioritized lower for resolving issues.[176] The late addition of this caused a cascading effect of forcing teams outside of NFT to share an interface with a new subsystem, which negatively impacted costs and time requirements.[177]

C. JAXA'S *HAYABUSA 2* AT ASTEROID (162173) RYUGU

Hayabusa 2 is the successor to the *Hayabusa 1* mission. The objectives of the *Hayabusa 2* mission are to examine the C-type asteroid (162173) Ryugu, explore the origins of water and organic matter, and how planets were created "through the collision, destruction, and combination" of the small planets, or planetesimals, which are believed to have been formed first.[178] It launched in 2014, arrived at asteroid (162173) Ryugu in 2018, and successfully returned to Earth in 2020.[179] Asteroid (162173) Ryugu is shown in Figure 22.

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[174] Lorenz et al., 6.

[175] Lorenz et al., 6.

[176] Lorenz et al., 6.

[177] Lorenz et al., 6.

[178] "Asteroid Explorer Hayabusa2," Institute of Space and Astronautical Space (ISAS), 2015, https://www.isas.jaxa.jp/en/missions/spacecraft/current/hayabusa2.html.

[179] Institute of Space and Astronautical Space (ISAS).

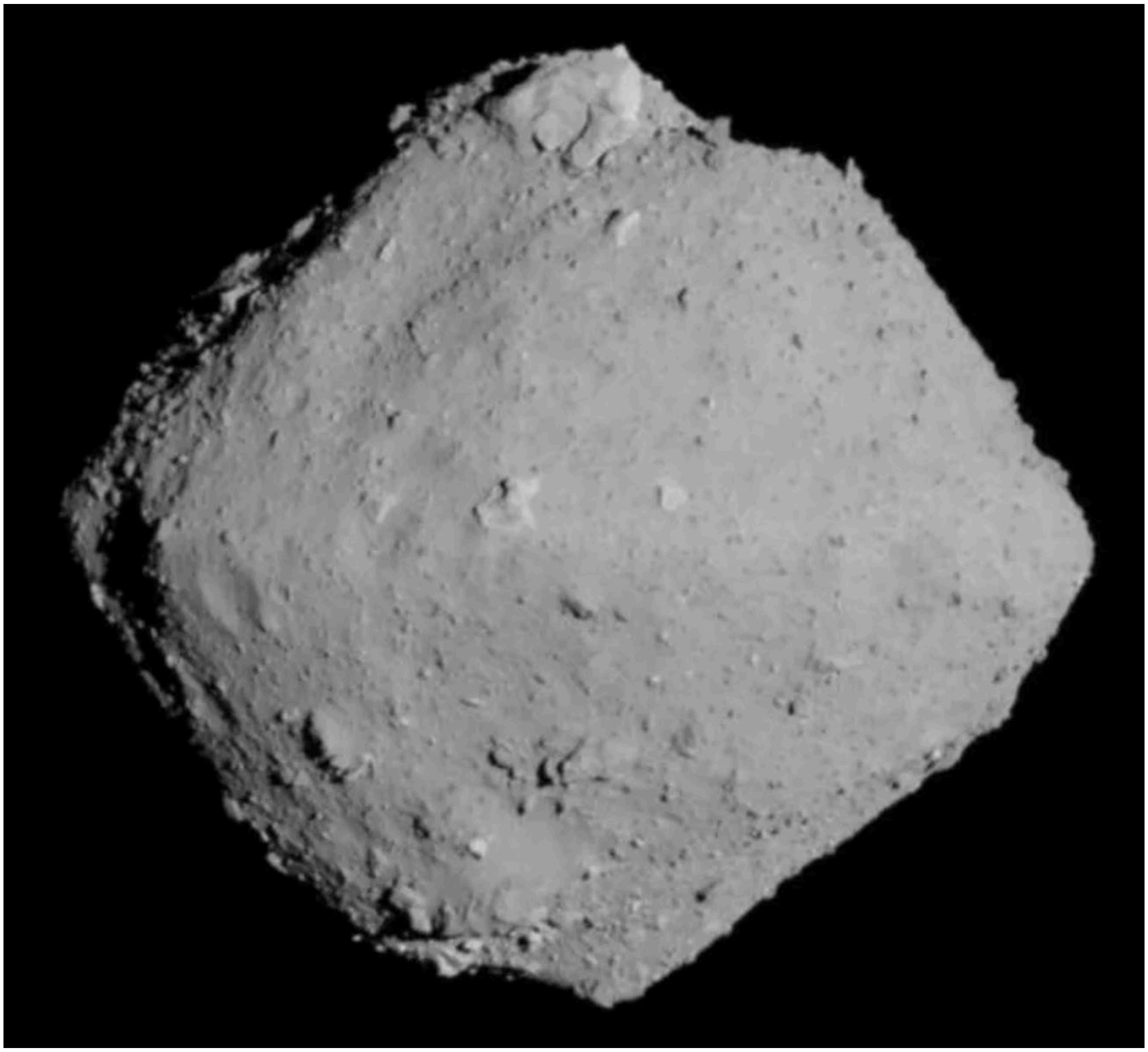

Figure 22. An Image of Asteroid (162173) Ryugu180

The main instruments onboard were the sampler mechanism, re-entry capsule, LIDAR, scientific mission equipment (near infrared and thermal infrared), impactor, and rover (MINERVA-II).[181] What was unique about this sample return mission was the way in which the asteroid sample was collected. *Hayabusa 2* fired its impactor into the Ryugu's surface. This created a crater, exposed Ryugu's subsurface, and enabled *Hayabusa 2* to

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[180] Source: Paul K. Byrne, "Touching the Asteroid Ryugu Revealed Secrets of Its Surface and Changing Orbit," The Conversation, May 7, 2020, http://theconversation.com/touching-the-asteroid-ryugu-revealed-secrets-of-its-surface-and-changing-orbit-137852.

[181] "Asteroid Explorer Hayabusa2."

collect material from underneath the surface of the asteroid.[182] Figure 23 shows an image before and after impact.

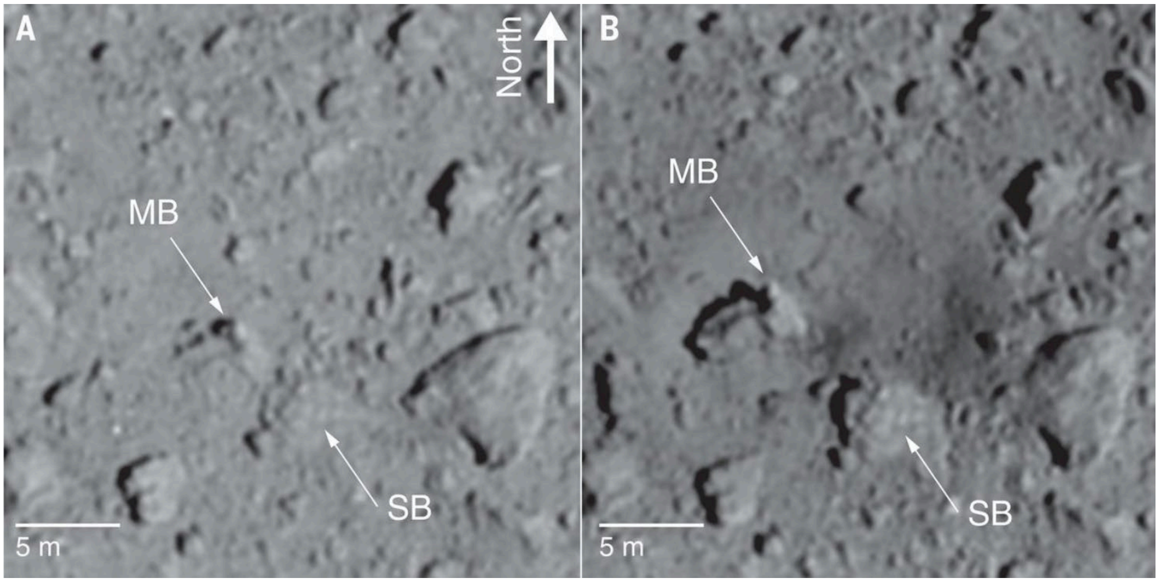

Figure 23. An Image of Ryugu Before Impact (Left) and an Image of Ryugu After Impact (Right)183

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[182] M. Arakawa et al., "An Artificial Impact on the Asteroid (162173) Ryugu Formed a Crater in the Gravity-Dominated Regime," *Science* 368, no. 6486 (April 3, 2020): 67, https://doi.org/10.1126/science.aaz1701.

[183] Source: Arakawa et al., 67.

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IV. SURVEY OF OTHER TECHNOLOGIES

A. ASTEROID MINING PROCESS

The five top level steps of extracting water from a NEA are: prospecting, excavation, processing, extraction, and storage.[184] Prospecting involves identifying, characterizing, and determining the value and feasibility of mining an asteroid. Excavation involves the process of retrieving minerals and ore from the asteroid regolith. Processing then involves separating the desired materials from the unwanted parts of the ore obtained. Once the ore is obtained, any valuable metals or water is extracted from the asteroid material. Finally, the water, minerals, or metals extracted must be stored safely without contamination during the storage phase for a return trip to Earth or for future applications in the spacecraft. Table 2 further details these steps and states its application to asteroids.

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[184] Kris Zacny et al., "Asteroid Mining," in *AIAA SPACE 2013 Conference and Exposition* (AIAA SPACE 2013 Conference and Exposition, San Diego, CA: American Institute of Aeronautics and Astronautics, 2013), 6, https://doi.org/10.2514/6.2013-5304.

Table 2. Steps for Asteroid Resource Extraction[185]

Step	Description	Application to Asteroids
Prospecting	Finding and defining the extent, location, and value of the ore body.	Mineral concentration may be assumed to be relatively uniform on asteroids, unless some minerals are preferentially present in the fine or coarse fraction of regolith.
Excavation	Mining minerals from the ore body • Pneumatic methods • Magnetic methods (iron-nickel dust, nano-phase iron) • Auger, scoop, etc.	Options include excavating and extracting in situ, excavation ore for delivery to an extraction plant, or capturing the entire asteroid for delivery to an extraction plant.
Processing	Comminution is a particle size reduction of materials. It is extremely energy inefficient process and hence should be limited or eliminated altogether. Concentration is process of increasing the concentration of the wanted minerals. This includes magnetic and electrostatic separation.	Magnetic materials could be extracted using magnetic concentration process. Only fines should be captured using for example a magnetic rake. Electrostatic separation will be able to capture fines only and leave out larger rocks.
Extraction	Minerals: Extraction of valuable metals from their ores through chemical or mechanical means.	If carbonaceous chondrite – water plus mineral extraction (titanium from Ilmenite, nano-phase iron) If metallic - difficult to de-alloy, hence use iron-nickel dust for 3D printing (structures can be much weaker in space than at 1g and no launch loads)
	Alloyed Metals: If metals are present in alloy form (e.g. Nickel-Iron) they must be de-alloyed.	
Storage	The refined resources is captured and stored within protective enclosure	Volatiles could be pressurized. Water is most likely going to be stored within pressure cylinders (so that it could be easily heated up and melted/sublimed). Processed ore could be stored in sealed containers to prevent losses.

There are several mass determination techniques during the prospecting phase of an asteroid retrieval mission. The first technique utilizes perturbations on neighboring spacecraft and provides the asteroid mass, close approach distance, relative velocity, and hundreds of other critical parameters that may affect the spacecraft.[186] Britt et al. further explains this mass determination technique:

> The heliocentric change in velocity of an asteroid or spacecraft after a close asteroid approach is directly proportional to the mass of the perturbing asteroid and inversely proportional to both the close approach distance and relative velocity of the two bodies. For a perturbed spacecraft, the line-of-sight component of this velocity change is determined by observing the change in the Doppler tracking data during a close encounter. The close

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[185] Source: Zacny et al., 6.

[186] Britt et al., “Asteroid Density, Porosity, and Structure,” 488.

> approach distance and relative velocity are determined from a spacecraft orbital solution that includes not only the spacecraft Doppler and range data but also the optical images of the asteroid before, during, and after the close flyby.[187]

The second mass determination technique uses the motions of an object's natural satellites. *Galileo's* imaging data of 243 Ida and its satellite Dactyl "estimated the mass, volume, and bulk density for Ida."[188]

Britt et al. further describes a third mass determination technique by analyzing the perturbations of asteroids on the motion of Mars:

> For perturbations with periods of 10 years or less, only Ceres, Pallas, and Vesta produce perturbative amplitudes of more than 50 m on the motion of Mars…Although other, smaller asteroids had nonnegligible effects upon the orbit of Mars, a direct solution for their individual masses were not feasible because their perturbative effects were not substantially larger than the observational accuracy…A mass was computed for each of a few hundred of the largest asteroids by using its estimated diameter and assuming a particular bulk density based upon its spectral class. By accumulating the perturbations of each spectral class together, it was possible to solve for the mean bulk density for the spectral class as a whole.[189]

B. VOLATILES INVESTIGATING POLAR EXPLORATION ROVER (VIPER)

The goal of NASA's VIPER is to continue the exploration for the presence of water and ice on the surface and subsurface of the Moon.[190] Past exploration missions have revealed that water and ice exist on the Moon. However, for humans to be able to access and extract this critical resource, future robots or astronauts will need to know exactly where it resides.[191]

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[187] Britt et al., 488.

[188] Britt et al., 488.

[189] Britt et al., 488.

[190] Rick Chen, "VIPER Mission Overview," Text, NASA, June 10, 2020, http://www.nasa.gov/viper/overview.

[191] Chen.

The VIPER is approximately the size of a golf cart.[192] Its primary drill and science instruments are the Neutron Spectrometer System (NSS), The Regolith and Ice Drill for Exploring New Terrains (TRIDENT), Near-Infrared Volatiles Spectrometer System (NIRVSS), and Mass Spectrometer Observing Lunar Operations (MSolo).[193] The NSS will be used to detect water down to three feet below the surface of the Moon.[194] TRIDENT drills into the subsurface of the Moon and transports it onto the surface.[195] NIRVSS then uses its spectrometer to evaluate the hydrogen content of the lunar surface material, determining the water content.[196] MSolo operates simultaneously with NIRVSS to measure and determine the water content of lunar surface material.[197] A conceptual drawing of VIPER is illustrated in Figure 24.

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[192] Rick Chen, "VIPER: The Rover and Its Onboard Toolkit," NASA, June 10, 2020, https://www.nasa.gov/viper/rover#KeyFeatures.

[193] Chen.

[194] Chen.

[195] Chen.

[196] Chen.

[197] Chen.

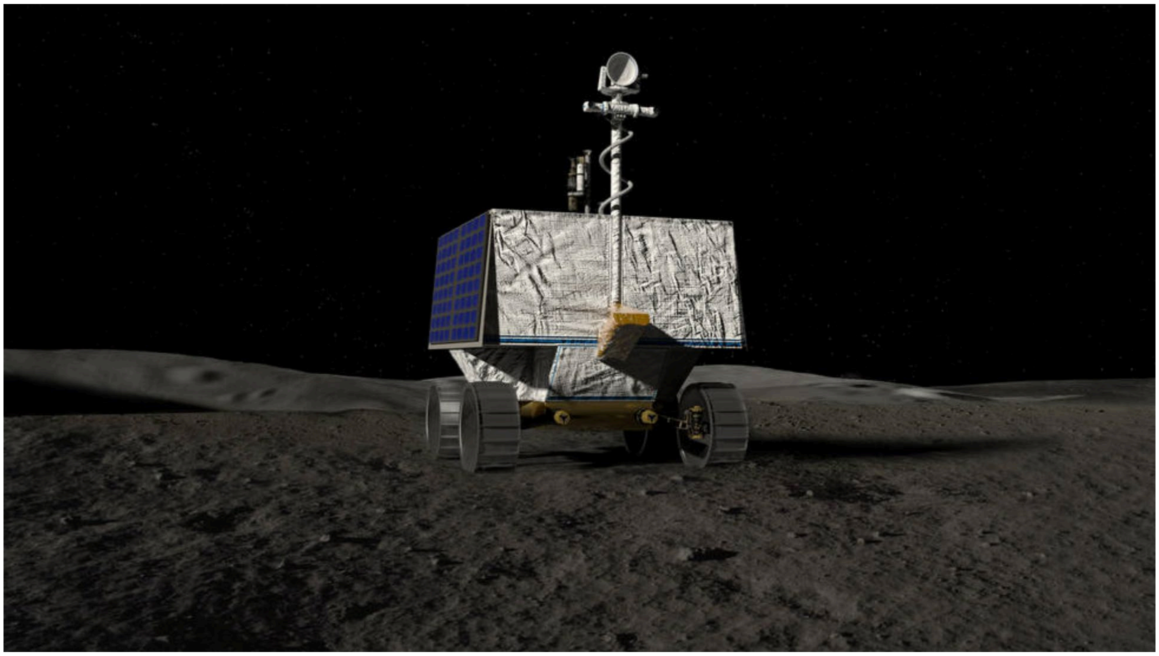

Figure 24. An Artist's Concept of VIPER: The Rover and Its Onboard Toolkit[198]

C. TECHNOLOGIES DEVELOPED FOR THE MOON

Of the twenty different processes that have been proposed for water to be extracted from the Moon, McKay and Allen demonstrated that the "simplest and best-studied [process] is the reduction of iron oxide in minerals and glass, using hydrogen gas."[199]

$$FeO + H_2 \rightarrow Fe + H_2O$$

McKay and Allen further explains this two-step process of "hydrogen reduction of lunar materials":

> Iron oxide (FeO) is first reduced and oxygen is liberated to form water…If oxygen, rather than water, is desired the water can be electrolyzed. Hydrogen is recycled to the reactor and oxygen is liquefied and stored.[200]

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[198] Source: Chen.

[199] David S. McKay and Carlton C. Allen, "Manufacturing Water on the Moon," in *Space Programs and Technologies Conference* (Space Programs and Technologies Conference, Huntsville, AL: American Institute of Aeronautics and Astronautics, 1995), https://doi.org/10.2514/6.1995-4065.

[200] McKay and Allen.

There are various types of lunar materials that water can be extracted from, such as lunar rocks, soil, and volcanic glass. Reduction experiments were performed on basalt, anorthositic breccia, and anorthositic gabbro with promising results shown below:

> Reduction of FeO to metal was demonstrated experimentally in basalt, anorthositic breccia, and anorthositic gabbro…A 10 g sample [of mare basalt 70035] was crushed, split, and reduced with hydrogen in experiments at 900–1050°C and pressures of 10^5–10^6 Pa (14.7-150 psia). In all tests, evolution of water began immediately and was essentially complete in 30–50 minutes.[201]

Breccias are "consolidated fragmental rocks…formed during meteoroid impacts."[202] Lunar basalt is volcanic rock and found primarily in the lower elevation areas of the Earth-facing side of the Moon, comprising of approximately 26% that side, whereas only 2% is found on the opposite facing side.[203]

McKay and Allen conducted Apollo 17 soil 74241 reduction experiments with the following methodology and results:

> The sample was reacted with flowing hydrogen at 800°C for 3 hours. Of the total iron content in the starting sample, 17% was metal with the remainder as FeO in pyroxene, olivine, and ilmenite. After reduction the iron metal content increased to 40% of the total iron, mainly at the expense of ilmenite. Our group reduced samples of mare soil 75061 in hydrogen 900–1500°C…The dominant source of water in these experiments was ilmenite, with lesser contributions from olivine and pyroxene. Yields proved to be only weakly dependent on temperature. Initial weight loss rates from three of these experiments were used to derive the activation energy of the reduction process, 7.4 kcal/mol.[204]

The main takeaway from McKay and Allen's reduction experiment was that it illustrated a strong correlation between FeO abundance and water yield, depicted in Figure 25.[205]

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[201] McKay and Allen.

[202] Taylor et al., "Lunar Rocks," 185.

[203] "Lunar Rocks," Smithsonian National Air and Space Museum, accessed February 21, 2021, https://airandspace.si.edu/exhibitions/apollo-to-the-moon/online/science/lunar-rocks.cfm.

[204] McKay and Allen, "Manufacturing Water on the Moon."

[205] McKay and Allen.

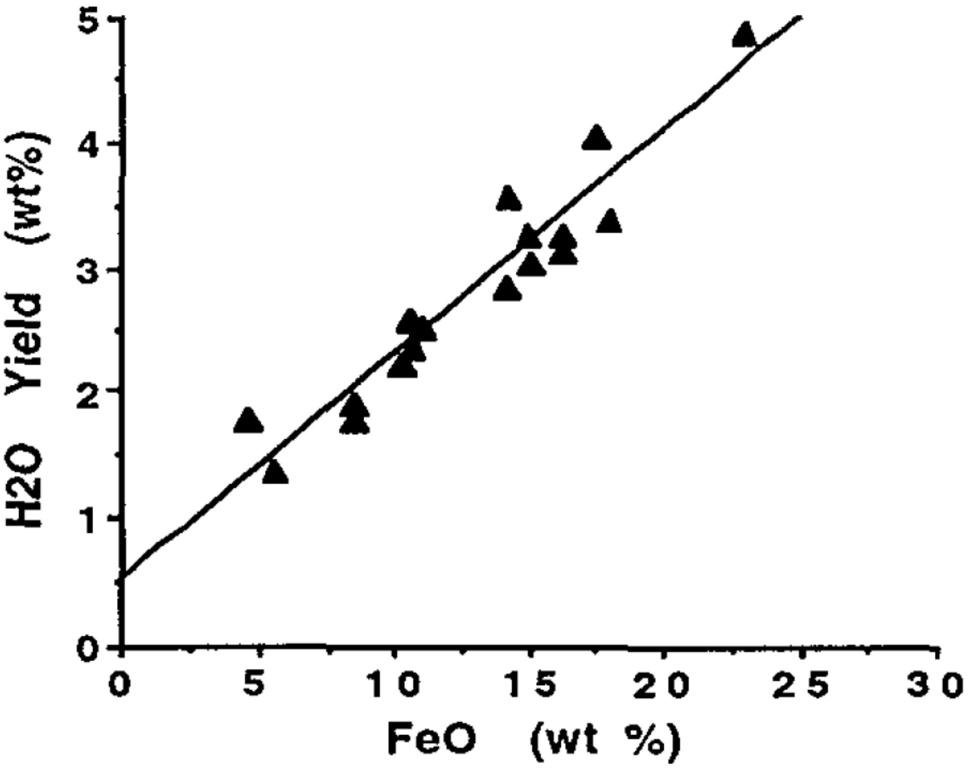

Figure 25. Lunar Soil Experiments at 1050°C206

McKay and Allen conclude that producing water on the Moon from surface materials is a reality.[207] This is in part possible due to the recent confirmed discovery of water on the Moon in 2008 by India's space agency, Indian Space Research Organization, and its spacecraft, the Chandrayaan-1.[208] This technology will be a critical step in providing water to space exploration missions for human life support, shielding, and to be processed into propellant.

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[206] Source: McKay and Allen.

[207] McKay and Allen.

[208] Jatan Mehta, "Your Guide to Water on the Moon," The Planetary Society, November 23, 2020, https://www.planetary.org/articles/water-on-the-moon-guide.

V. ECONOMIC DIMENSION

The prospect of profitably mining NEAs has been proposed for many years. The possible benefits of a sustainable and economically viable asteroid mining architecture are immense. Applications such as propellant, construction, and life support systems are some of many possible uses for extracting metals and volatiles from NEAs.[209] Due to the extensive risks and costs of an asteroid mining architecture, the ideal resource to mine is one that has a high value to mass ratio, such as water and rare earth metals.[210] The following subsections will survey a broad spectrum of economic viability studies.

A. COST ANALYSIS OF PREVIOUS MISSIONS

1. JAXA's *Hayabusa* Sample Return Mission to Asteroid (25143) Itokawa

The total cost of the *Hayabusa* sample return mission was estimated at $150 million.[211] The cost of the spacecraft was approximately $100 million.[212] Amplifying information regarding the cost of the mission was not available to the author.

2. Near-Earth Asteroid Rendezvous (*NEAR*) Shoemaker Mission

NASA's *NEAR* mission is famous because it marked the first time any spacecraft orbited and landed on a celestial body, asteroid (433) Eros, which was a remarkable achievement for the United States. As stated previously, this was the same spacecraft that conducted a successfully fly-by of asteroid (253) Mathilde. An image of 433 Eros is depicted in Figure 26, and an illustration of the three-point landing on Eros' surface is shown in Figure 27.

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[209] Hein, Matheson, and Fries, "A Techno-Economic Analysis of Asteroid Mining," 104.

[210] Hein, Matheson, and Fries, 104.

[211] "Hayabusa," Astronautix, 2019, http://www.astronautix.com/h/hayabusa.html.

[212] Astronautix.

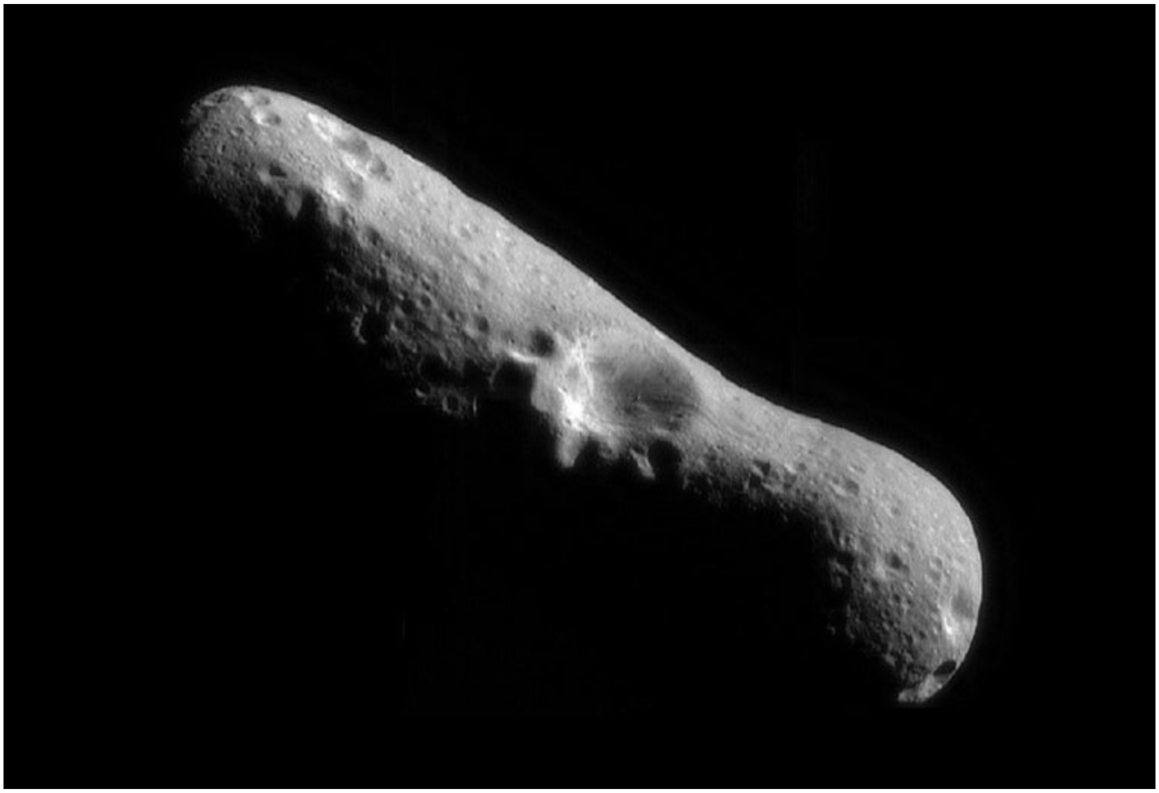

Figure 26. A Mosaic of Four Images Obtained by NASA's NEAR Spacecraft[213]

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[213] Source: "433 Eros," NASA Solar System Exploration, December 19, 2019, https://solarsystem.nasa.gov/asteroids-comets-and-meteors/asteroids/433-eros/in-depth.

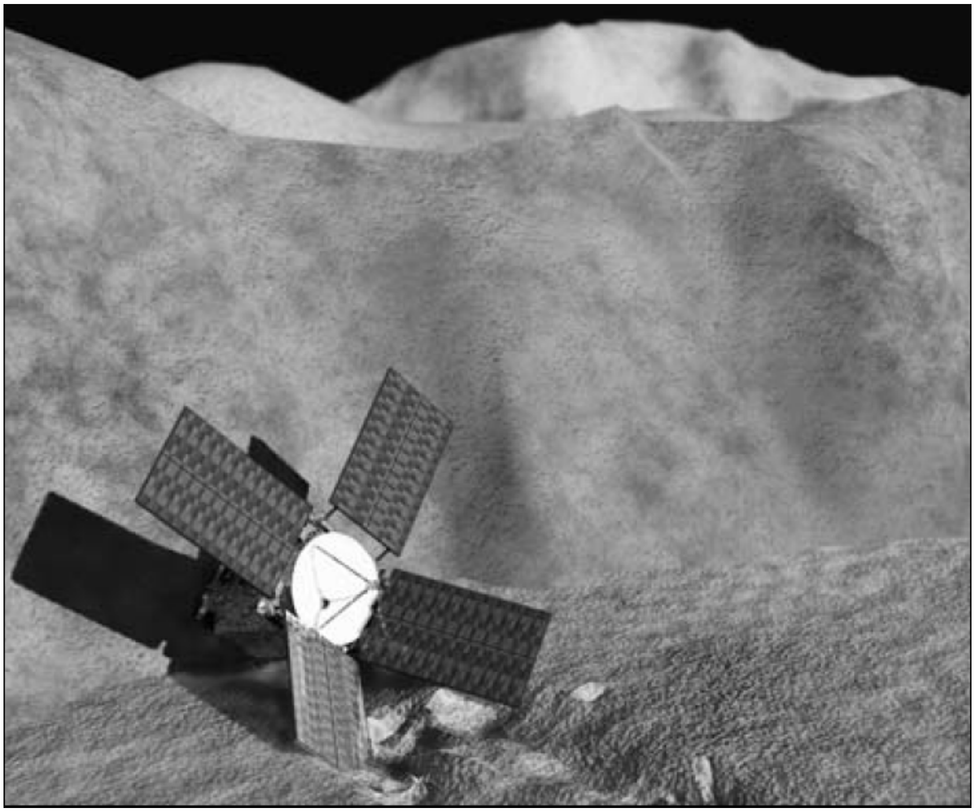

Figure 27. Illustration of the NEAR Spacecraft's Three-Point Landing on 433 Eros214

The total mission costs of *NEAR* is 220.5 million of real-year dollars, shown in Table 3.[215] The spacecraft flight systems and microrover mission operations after launch were the majority of the costs at 79.1 and 60.8 million of real-year dollars, respectively.[216] Some of the key themes of reducing costs were designing for simplicity and saving through miniaturization.[217]

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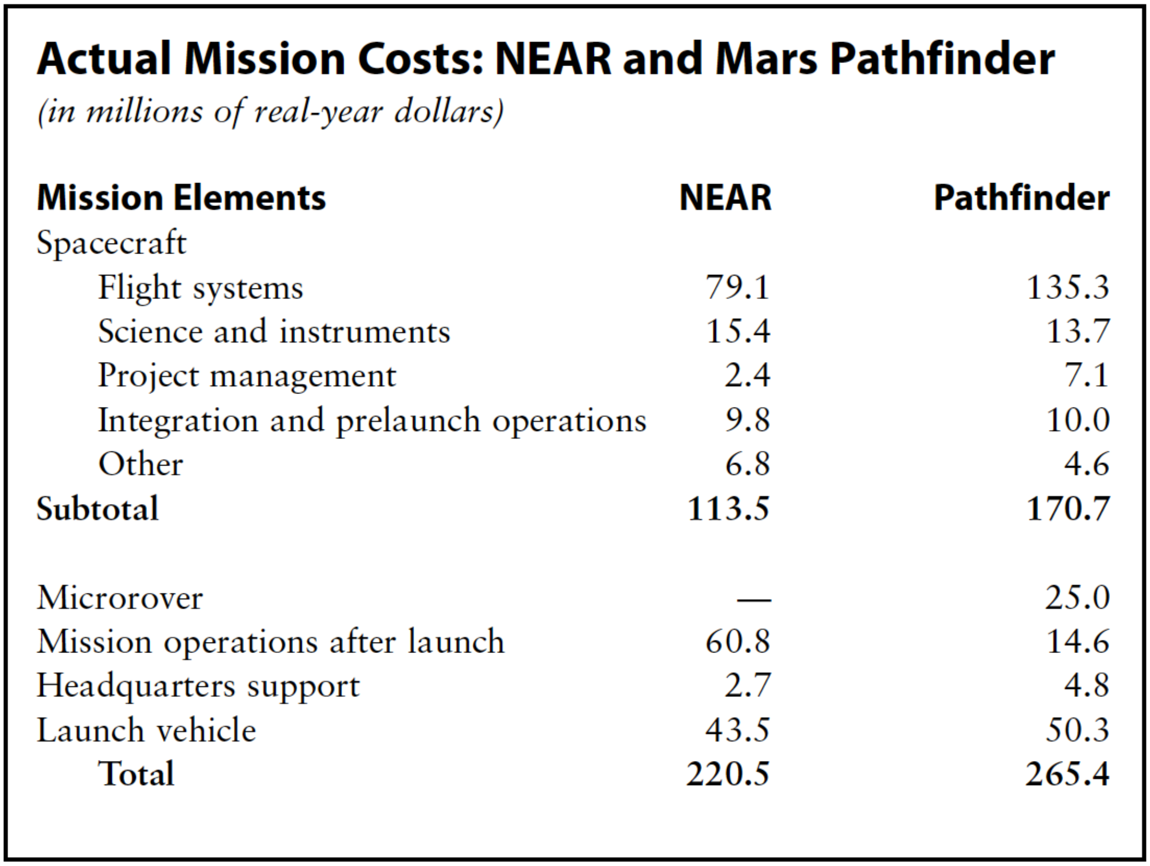
[214] Source: Howard E. McCurdy, "Low-Cost Innovation in Spaceflight: The Near Earth Asteroid Rendezvous (NEAR) Shoemaker Mission," 2005, 49.

[215] McCurdy, 22.

[216] McCurdy, 22.

[217] McCurdy, 19, 22.

Table 3. Total Mission Costs of *NEAR* in Real-Year Dollars[218]



Actual Mission Costs: NEAR and Mars Pathfinder

(in millions of real-year dollars)

Mission Elements	**NEAR**	**Pathfinder**
Spacecraft		
Flight systems	79.1	135.3
Science and instruments	15.4	13.7
Project management	2.4	7.1
Integration and prelaunch operations	9.8	10.0
Other	6.8	4.6
Subtotal	**113.5**	**170.7**
Microrover	—	25.0
Mission operations after launch	60.8	14.6
Headquarters support	2.7	4.8
Launch vehicle	43.5	50.3
Total	**220.5**	**265.4**

The total instrument costs and its cost breakdown are shown in Table 4. The gamma-ray spectrometer and instrument data-processing units comprised most of the cost at 4.8 and 4.5 million of real-year dollars.[219]

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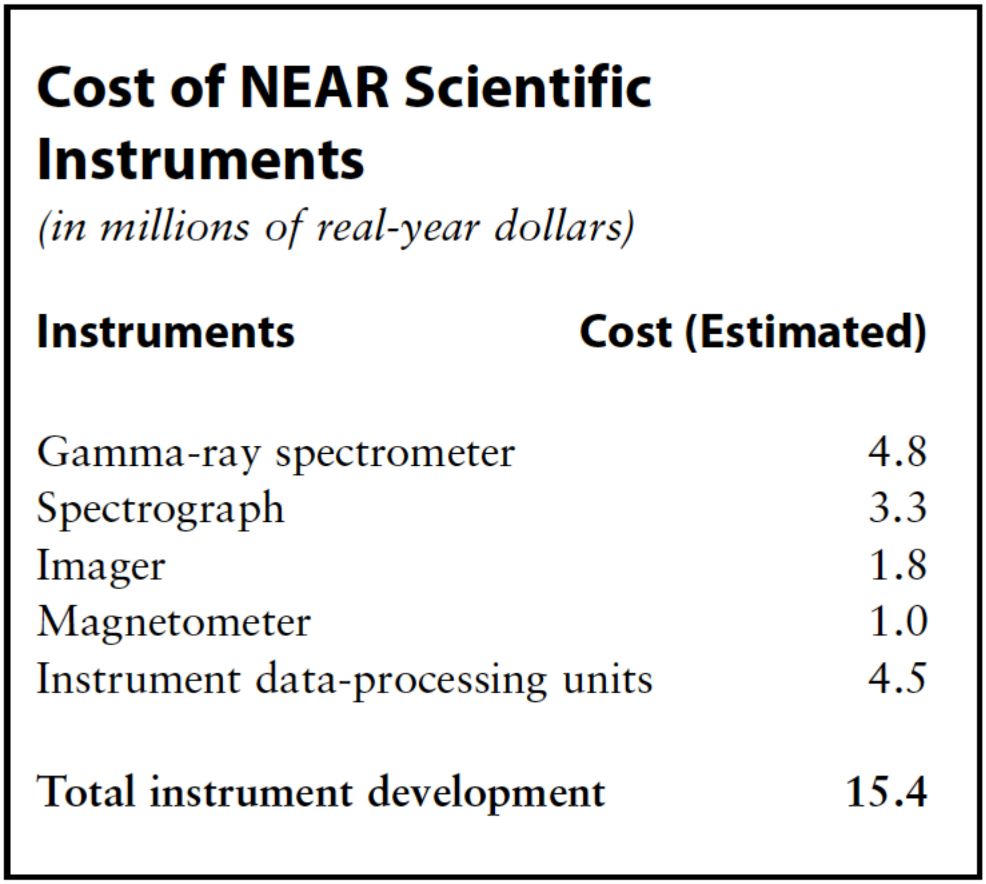
[218] Source: McCurdy, 22.

[219] McCurdy, 23.

Table 4. Cost of *NEAR* Scientific Instruments[220]



Cost of NEAR Scientific Instruments

(in millions of real-year dollars)

Instruments	Cost (Estimated)
Gamma-ray spectrometer	4.8
Spectrograph	3.3
Imager	1.8
Magnetometer	1.0
Instrument data-processing units	4.5
Total instrument development	**15.4**

The main lesson of the *NEAR* mission is that there is a relatively low-cost viable alternative to space travel in the solar system.[221] Similar to other highly technical endeavors, the *NEAR* project team and scientists had to balance money and time with a demanding schedule.[222] Yet, they were able to successfully create the first spacecraft to orbit and land on an asteroid.[223] Applied Physics Laboratory (APL) relied heavily on small project teams, colocation of team members, extensive direct work with the spacecraft, and

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[220] Source: McCurdy, 23.

[221] McCurdy, 56.

[222] McCurdy, 57.

[223] McCurdy, 56.

a seamless integration among management, designers, fabricators, and members of the operations team—there was no division of accountability.[224]

3. *OSIRIS-REx* Mission to Asteroid (101955) Bennu

In 2016, the *OSIRIS-REx* mission launched and is expected to return surface material from Bennu's surface in 2023.[225] The total cost of the *OSIRIS-REx* mission is expected to be $1.16 billion.[226] The spacecraft costed $558.5 million; launch, $183.5 million; and mission operations (9 years), $283 million, as shown in Table 5.[227]

Table 5. Total Cost of *OSIRIS-REx* Mission[228]

Spacecraft Development	$558.5 million
Launch (Atlas V 411)	$183.5 million
Mission Operations (9 years)	$283 million
Total	**$1.16 billion**

B. COSTS OF EXTRACTING RESOURCES FROM NEAS

1. Asteroid Mining with an Architecture of Small Spacecraft

There has been discussion for decades on the economic viability of extracting vital resources such as water and precious metals from NEAs. Furthermore, there have been numerous methods and architectures proposed to make asteroid mining economically viable. For instance, Calla et al. concluded that an architecture of approximately 200 small spacecraft could enable economically viable mining operations within 10 years of

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[224] McCurdy, 56.

[225] "OSIRIS-REx," NASA, April 14, 2021, https://www.nasa.gov/osiris-rex.

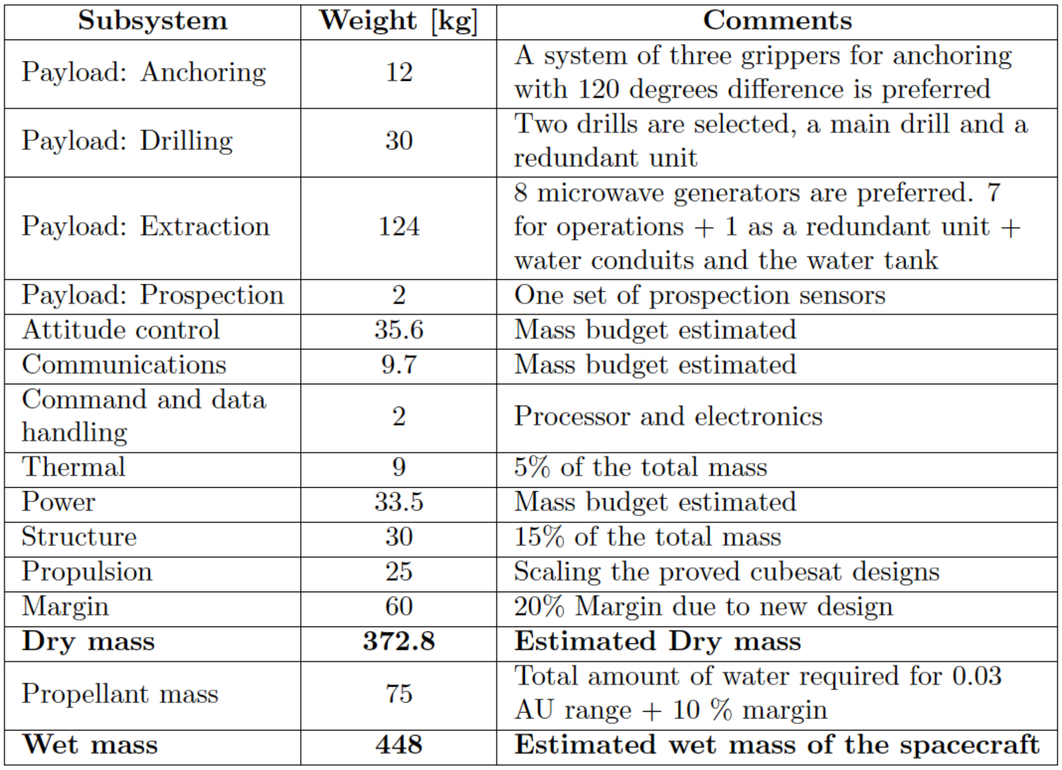
[226] "Cost of OSIRIS-REx," The Planetary Society, accessed May 4, 2021, https://www.planetary.org/space-policy/cost-of-osiris-rex.

[227] The Planetary Society.

[228] Source: The Planetary Society.

operation.[229] Calla et al. defined a "small" spacecraft as at or below 500 kg.[230] The complete mass budget is shown in Table 6. In order for this architecture to break-even, the up-front investment would be approximately $7 billion.[231] For perspective, this is below other major acquisitions in the economy (e.g. Amazon acquired Whole Foods for $13.7 billion and Vision Fund raised $93 billion during its funding round).[232] The first spacecraft payload and bus is estimated to cost $48.8 and $64.8 million, respectively.[233] These cost breakdowns are shown in Table 7 and Table 8.

Table 6. Small Spacecraft Mass Budget[234]



Subsystem	**Weight [kg]**	**Comments**
Payload: Anchoring	12	A system of three grippers for anchoring with 120 degrees difference is preferred
Payload: Drilling	30	Two drills are selected, a main drill and a redundant unit
Payload: Extraction	124	8 microwave generators are preferred. 7 for operations + 1 as a redundant unit + water conduits and the water tank
Payload: Prospection	2	One set of prospection sensors
Attitude control	35.6	Mass budget estimated
Communications	9.7	Mass budget estimated
Command and data handling	2	Processor and electronics
Thermal	9	5% of the total mass
Power	33.5	Mass budget estimated
Structure	30	15% of the total mass
Propulsion	25	Scaling the proved cubesat designs
Margin	60	20% Margin due to new design
Dry mass	**372.8**	**Estimated Dry mass**
Propellant mass	75	Total amount of water required for 0.03 AU range + 10 % margin
Wet mass	**448**	**Estimated wet mass of the spacecraft**

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[229] Calla, Fries, and Welch, "Asteroid Mining with Small Spacecraft and Its Economic Feasibility," 17.

[230] Calla, Fries, and Welch, 12.

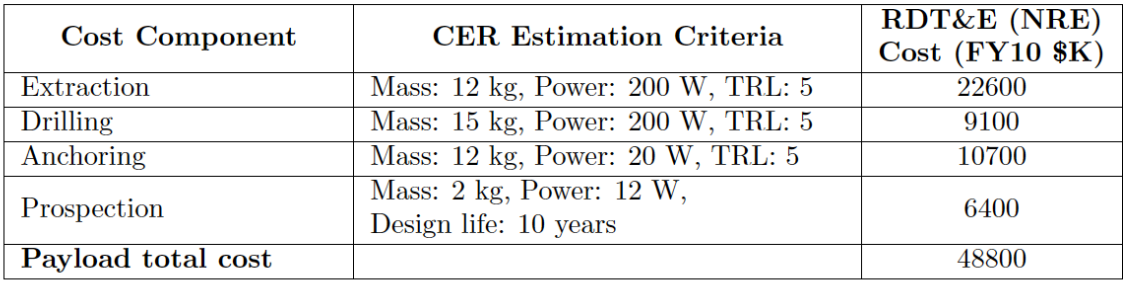
[231] Calla, Fries, and Welch, 17.

[232] Calla, Fries, and Welch, 17.

[233] Calla, Fries, and Welch, 14.

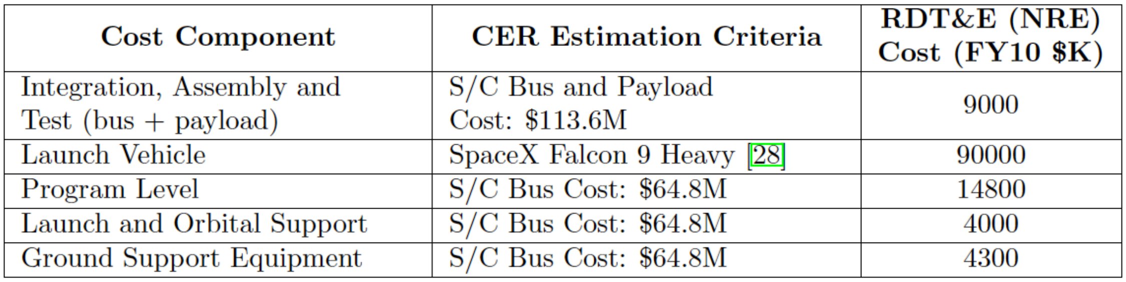
[234] Source: Calla, Fries, and Welch, 12.

Table 7. Cost Estimation of the Payload[235]



Cost Component	**CER Estimation Criteria**	**RDT&E (NRE) Cost (FY10 $K)**
Extraction	Mass: 12 kg, Power: 200 W, TRL: 5	22600
Drilling	Mass: 15 kg, Power: 200 W, TRL: 5	9100
Anchoring	Mass: 12 kg, Power: 20 W, TRL: 5	10700
Prospection	Mass: 2 kg, Power: 12 W, Design life: 10 years	6400
Payload total cost		48800

Table 8. Cost Estimation of the Bus[236]



Cost Component	**CER Estimation Criteria**	**RDT&E (NRE) Cost (FY10 $K)**
Integration, Assembly and Test (bus + payload)	S/C Bus and Payload Cost: $113.6M	9000
Launch Vehicle	SpaceX Falcon 9 Heavy [28]	90000
Program Level	S/C Bus Cost: $64.8M	14800
Launch and Orbital Support	S/C Bus Cost: $64.8M	4000
Ground Support Equipment	S/C Bus Cost: $64.8M	4300

After performing an economic return analysis of the proposed architecture, break-even points (profit) were identified. Figure 28 illustrates cost and revenues for one, 50, 200, and 400 spacecraft with respect to the number of years of operation. An intersection between the solid black line with the shaded region indicates an economically viable option with a 95% confidence interval.[237] Calla et al. proposes that a fleet of a higher quantity of smaller spacecraft will enable profitability earlier than an architecture of less, more expensive spacecraft. As shown in Figure 28, Calla et al. illustrate that a fleet of 400 water mining spacecraft will achieve profitability in approximately six years, whereas a smaller fleet of 50 water mining spacecraft for water utilization at various orbits will achieve profitability in approximately 10 years.[238]

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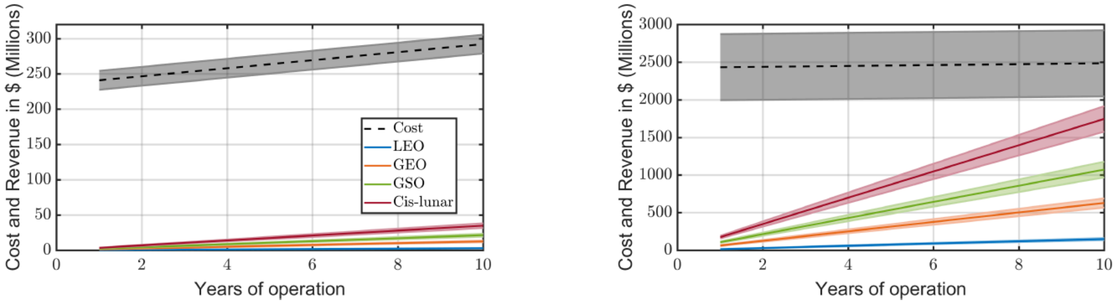
[235] Source: Calla, Fries, and Welch, 14.

[236] Source: Calla, Fries, and Welch, 14.

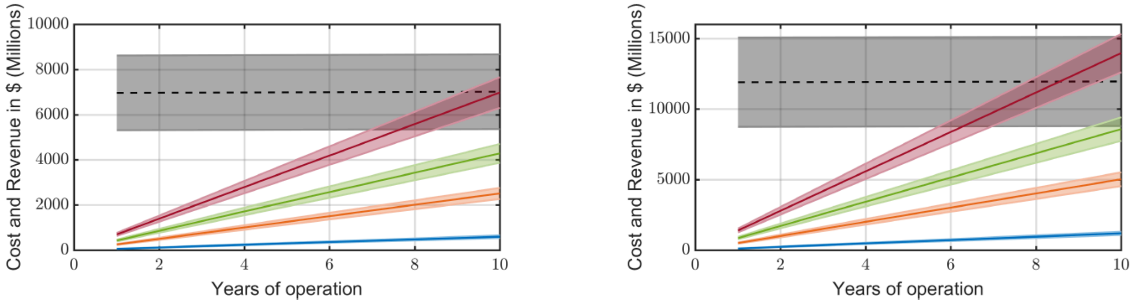
[237] Calla, Fries, and Welch, 17.

[238] Calla, Fries, and Welch, 17.



(a) One water mining spacecraft.

(b) 50 water mining spacecraft.



(c) 200 water mining spacecraft.

(d) 400 water mining spacecraft.

Figure 28. Cost Analysis and Economic Return[239]

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[239] Source: Calla, Fries, and Welch, 17.

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VI. SURVEY OF POLITICAL DIMENSION

A. INTERNATIONAL SPACE NORMS, POLICIES, AND TREATIES

1. 1967 Outer Space Treaty (OST)

The overarching theme of the 1967 Outer Space Treaty promotes the exploration and use of outer space in the interest of all mankind.[240] However, there are two key conflicting policies established in the OST. The 1967 Outer Space Treaty governs the activities of countries in the exploration and use of outer space, the Moon, and celestial bodies.[241] Article I of the OST establishes that "there shall be freedom of scientific investigation in outer space," regardless of any economic incentive.[242] However, Article II states that nothing on the surface of the Moon or other celestial body may be "subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means."[243] Essentially, the overarching theme of the OST appears to promote the unfettered peaceful access to and use of space, but Article II prohibits any type of appropriation by any state. These conflicting guidelines may present political challenges on the international stage as progress towards the commercialization of space accelerates. Recommendations to prevent this future point of conflict are made in Chapter VII "Analysis."

2. The 1979 Moon Agreement

In accordance with the Charter of the United Nations, the 1979 Agreement Governing the Activities of States on the Moon and Other Celestial Bodies, "The Moon Agreement" is a multilateral treaty that promotes the peaceful use of the Moon for the advancement of science and mankind. This is important because the Moon is the nearest celestial body to the Earth and will be a vital resource in future space exploration. Article

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[240] "Outer Space Treaty," United Nations: Office for Outer Space Affairs, December 19, 1966, https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/outerspacetreaty.html.

[241] United Nations: Office for Outer Space Affairs.

[242] United Nations: Office for Outer Space Affairs.

[243] United Nations: Office for Outer Space Affairs.

4 of the Moon Agreement establishes that the "exploration and use of the moon shall be the providence of all mankind and shall be carried out for the benefit and in the interests of all countries, irrespective of their degree of economic or scientific development."[244]

The Moon Agreement also potentially presents future political tension in straying from Article II of the OST. In order to establish a lunar base and improve water extraction techniques on the Moon, a country may need to lay claim on part of the Moon's surface. Once a lunar base is established to harvest the Moon's resources, this process may be perceived to violate Article II of the OST. Any resources extracted from the Moon or a celestial body may be assumed to belong to the country. However, Article II of the OST prohibits a claim on any part of the Moon or celestial bodies by "means of use or occupation, or by any other means."[245]

3. The 2020 U.S. National Space Policy

The 2020 National Space Policy is the most current national level space policy for the United States and establishes the principles, goals, and guidelines for space operations. Principles in the 2020 National Space Policy that directly relate to the future direction of asteroid mining include: encouraging unfettered access to space in support of scientific and economic advancement for all humanity; facilitating a robust and competitive commercial space sector; and concurring with the OST guidelines regarding the inability of countries to appropriate any celestial body in outer space.[246]

The goals established in the United States 2020 National Space Policy that facilitate further asteroid mining technology development include: incentivizing the private industry; encouraging and expanding international space cooperation and mutually beneficial space activities; and increasing human activity into deep space.[247]

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[244] Special Political Committee, *Agreement Governing the Activities of States on the Moon and Other Celestial Bodies* (United Nations: Office for Outer Space Affairs: Special Political Committee, 1979), 78.

[245] United Nations: Office for Outer Space Affairs, "Outer Space Treaty."

[246] White House, *National Space Policy of the United States of America* (Washington, DC: White House, 2020), 3, https://trumpwhitehouse.archives.gov/wp-content/uploads/2020/12/National-Space-Policy.pdf.

[247] White House, 5.

Similar to the OST and Moon Agreement, there are contradicting principles in the U.S. 2020 National Space Policy that may cause future political strife internationally. One of the principles encourages economic freedom and space activities that may be profitable.[248] An example of this principle is "the extraction and utilization of space resources…for…commercial operations."[249] Another principle states that the United States "will seek to deter, counter, and defeat threats in the space domain that are hostile to [its] national interests."[250] For instance, the United States will deliberately respond to "any purposeful interference with…[its] space systems."[251] This includes, is not limited to, interference to the ground, link, or space segment of a satellite communication system, and non-kinetic to kinetic interference. And according to the 2021 U.S. Interim National Security Strategic Guidance, one of the core goals, or national interests, of the current administration is rebuilding the U.S. economic foundation.[252] However, one of the principles in the National Space Policy is recognizing a key tenant of the OST, which prohibits any claim of sovereignty of any part of the Moon or other celestial bodies by any means.[253]

4. NASA's Artemis Program

NASA's Artemis Program is an initiative to develop and establish a sustainable presence on the Moon by landing astronauts on the lunar south pole by 2024.[254] The long-term goal of the Artemis Program is to use the Moon as a fuel depot to eventually launch humans to Mars.[255] The Trump Administration's Space Policy Directive (SPD) 1 in 2019

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[248] White House, 3.

[249] White House, 3.

[250] White House, 4.

[251] White House, 4.

[252] White House, *Interim National Security Strategic Guidance* (Washington, DC: The White House, 2021), https://www.whitehouse.gov/wp-content/uploads/2021/03/NSC-1v2.pdf.

[253] White House, *National Space Policy of the United States of America*, 3.

[254] "Artemis, NASA's Moon Landing Program," The Planetary Society, 2021, https://www.planetary.org/space-missions/artemis.

[255] Planetary Society.

directed NASA to achieve this endeavor.[256] This program will bolster the commercial sector by working closely with the commercial sector to achieve its short and long-term objectives.

In support of future space resource utilization, the Artemis Accords aim to encourage spacefaring nations to follow the following key principles: peaceful relationships, transparency of policies, interoperability of systems, emergency assistance, registration of space objects, release of scientific data, protecting heritage, sustainable utilization of space resources, deconfliction of activities, and orbital debris and spacecraft disposal.[257] Furthermore, in 2020, the White House issued an Executive Order, "Encouraging International Support for the Recovery and Use of Space Resources," directing "the Secretary of State to lead a U.S. Government effort to develop joint statements, bilateral agreements, and multilateral instruments with like-minded foreign states."[258] This will be a critical effort for the United States politically and economically, as China has demonstrated its intention to establish a space-based economy.

5. China's Space Policy and Ambitions

China will be a major competitor in space and will present interesting political challenges to the United States. As stated in the 2019 Report to Congress of the U.S.-China Economic and Security Review Commission, China's goal is to "establish a leading position in the economic and military use of outer space" by 2040.[259] Additionally, China intends on establishing "a commanding position in the commercial launch…[sector] relying in part on aggressive state-backed financing" and leveraging the success of its "military-civil fusion strategy."[260] Finally, underpinning China's strategic goals in space

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[256] Planetary Society.

[257] NASA, "Artemis Plan," NASA, September 2020, 71–73, https://www.nasa.gov/sites/default/files/atoms/files/artemis_plan-20200921.pdf.

[258] NASA, 28.

[259] Economic and Security Review Commission, "China's Ambitions in Space - Contesting the Final Frontier" (United States: Congress, 2019), 359, https://www.uscc.gov/sites/default/files/2019-11/Chapter%204%20Section%203%20-%20China%E2%80%99s%20Ambitions%20in%20Space%20-%20Contesting%20the%20Final%20Frontier.pdf.

[260] Economic and Security Review Commission, 359.

is "establishing a commanding position in cislunar space…to reap the benefits of what Beijing views as its strategic value and the vast potential of the future space-based economy."[261]

China's goals in the final frontier will likely impact the U.S. military, economic, and political space hegemony. This will increase the chances of political friction between these two global superpowers. Article II of the OST prohibits any claim of sovereignty of the Moon. One key aspect of a Chinese space-based economy, however, may include mining scarce resources, such as water, off the Moon. Similar to any other country that may conduct mining operations, this action may be perceived as violating the OST, especially if China establishes a base on the Moon. Furthermore, military, economic, and political power is inextricably linked. These factors indicate clearer guidelines regarding the utilization of space resources may be required to prevent future political contention.

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[261] Economic and Security Review Commission, 362.

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VII. ANALYSIS

A. TECHNOLOGICAL FEASIBILITY

Asteroid mining will be technologically feasible in the near future. Three successful asteroid sample return missions from two different countries have already been conducted: Japan's *Hayabusa 1* at 25143 Itokawa, *Hayabusa 2* at 162173 Ryugu, and the United States' *OSIRIS-REx* at 101955 Bennu. Spacefaring nations have demonstrated the ability to travel to, characterize, safely land on, and collect from the surface of a NEA and safely return the asteroid sample back to Earth.

Therefore, the question is not, "Will asteroid mining ever be feasible?" Instead, a better question should be, "What key development should governments and companies prioritize in order to accelerate technical feasibility?" The answer to this also improves the chances of a profitable asteroid mining architecture. The key development that governments and commercial industries should focus on is perfecting the manufacturing of water not only on the Moon but also on NEAs. Refining the manufacturing of water in space will enable future sample return mission to collect much needed water for life support, shielding, and propellant.

As McKay and Allen have demonstrated, producing water "from lunar materials is now a reality."[262] Yields are predictable and the water-producing reactions occur on the order of tens of minutes.[263] Identifying the potential of lunar soil for the production of water can be determined from orbit.[264] However, just because their findings are a reality does not mean that the technology is ready to be used in an actual space architecture. McKay and Allen's findings illustrate that manufacturing water on the Moon is the closest next tangible technology that needs to be refined. This is because it will provide the highest chances of creating a profitable asteroid mining architecture, detailed in the next subsection, "Economic Benefit and Feasibility."

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[262] McKay and Allen, "Manufacturing Water on the Moon."

[263] McKay and Allen.

[264] McKay and Allen.

Another reason the focus should be on improving mobile in-situ water extraction systems is that it is feasible to develop, test, and evaluate these technologies on our nearby celestial neighbor, the Moon. Spudis and Lavoie concluded in their conference paper "Using the Resources of the Moon to Create a Permanent, Cislunar Space Faring System" that it is viable to begin exploring the practicality of implementing these technologies on the Moon.[265] Additionally, Zacny et al. demonstrated a mobile in-situ water extraction system that successfully extracted up to 92% of water from icy soil.[266] The next logical step is to implement these scientific breakthroughs on the Moon. Successfully producing water on the Moon would be an incredible scientific achievement and unlock numerous space exploration possibilities. Water would no longer have to be launched from the Earth's surface, a tremendous energy cost saving. The Moon will serve as a reliable testing ground for new technologies and scientific breakthroughs. It will act as a launching pad for various spacefaring missions, providing much-needed water for life support, shielding, and propellant. As Spudis and Lavoie stated, "eliminating the need to launch everything from the surface of the Earth [will] fundamentally change the paradigm of spaceflight."[267]

B. ECONOMIC FEASIBILITY

Asteroid mining is not economically profitable at this time due to launch and operation costs as well as the absence of the technology to profitably mine critical resources from NEAs. However, the manufacturing of water on the Moon or NEAs appears to have the best chance of improving profitability of an asteroid mining architecture. Zacny et al. concluded in 2012 that it is feasible to extract and produce 5 kg of water/day employing the In-Situ Resource Utilization (ISRU) under Mars conditions.[268] Improving this rate of water production will be a key step in enabling an economically feasible asteroid mining architecture.

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[265] Spudis and Lavoie, "Using the Resources of the Moon," 1.

[266] Kris Zacny et al., "Mobile In-Situ Water Extractor (MISWE) for Mars, Moon, and Asteroids In Situ Resource Utilization," in *AIAA SPACE 2012 Conference & Exposition* (AIAA SPACE 2012 Conference & Exposition, Pasadena, California: American Institute of Aeronautics and Astronautics, 2012), 1, https://doi.org/10.2514/6.2012-5168.

[267] Spudis and Lavoie, "Using the Resources of the Moon," 1.

[268] Zacny et al., "Mobile In-Situ Water Extractor (MISWE)," 20.

The cost of manufacturing water on the Moon or asteroids and returning it to Low Earth Orbit (LEO) has the potential to be drastically less expensive than transporting water from the Earth's surface into orbit. This is due to Earth's gravity well. NASA calculated that the cost of launching one gallon of water into LEO was $25,000 per gallon.[269] Launching from the Earth's surface into LEO will likely cost more than returning material from outer space into Earth's orbit. Lewis, in his book *Mining the Sky: Untold Riches from the Asteroids, Comets, and Planets*, proposed that manufacturing critical resources from lunar materials may be desirable "in order to minimize the need for expensive launches" from Earth's surface.[270] Another possibility is using the ISS as a depot, or "transportation hub," that stores water for future use.[271] Lewis elaborates on this possibility by stating that "using the space station as a transportation hub significantly reduces that mass that must be launched from Earth."[272]

The capability of mobile in-situ water extraction on the Moon will enable more profitable asteroid mining architectures. Calla et al. proposed that a break-even point for an architecture of 400 water mining spacecraft may occur in as early as six years.[273] A larger architecture of smaller spacecraft enables scalability and redundancy.[274] This would ultimately improve the economic feasibility of future asteroid mining operations. However, this would not be possible without first demonstrating a working proof of concept of successful water extraction from the Moon. A viable mobile in-situ water extraction system would not only enable profitable cislunar mining operations but also allow the Moon to serve as a fuel depot and launching pad for future deep space exploration missions for economic and scientific advancement of humanity.

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[269] NASA, "NASA - In-Line Water Filtration: Better Hygeine, Less Expense," accessed May 19, 2021, https://www.nasa.gov/topics/nasalife/pure_water.html.

[270] Lewis, *Mining the Sky: Untold Riches from the Asteroids, Comets, and Planets*, 57.

[271] Lewis, 71.

[272] Lewis, 71.

[273] Calla, Fries, and Welch, "Asteroid Mining," 17.

[274] Calla, Fries, and Welch, 17.

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VIII. RECOMMENDATION AND CONCLUSION

As Spudis and Lavoie concisely stated, removing the requirement to launch water, propellant, or any other critical resource from Earth will profoundly alter how we view the technical aspects and economics of spacefaring missions.[275] This thesis recommends further exploration and investment from commercial industries and the government into mobile in-situ water extraction systems on the Moon.

There is a new awakening to space. As John Lewis affirmed in his book *Mining the Sky: Untold Riches from the Asteroids, Comets, and Planets*, "Shortage of resources is not a fact; it is an illusion born of ignorance."[276] Advancements in the commercial space industry have greatly reduced the cost of access to space. However, there are still many areas to improve on in order to sustainably access the limitless supplies of resources in outer space, whether on asteroids, comets, or planets. Technological advancements must continue to be made in extracting water from asteroid conditions. Refining in-situ water extraction techniques is not only the next logical step in mining asteroids, this technology is also the key to unlocking the vast amounts of water in asteroids. Optimizing this technology will enable a more profitable asteroid mining architecture by providing a much needed resource in the form of life support, shielding, or most importantly, propellant.

Scientific and technological improvements will inevitably enable asteroid mining to be technically and economically feasible as long as the United States continues to push the boundaries of what is possible in space.[277]

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[275] Spudis and Lavoie, "Using the Resources of the Moon to Create a Permanent, Cislunar Space Fairing System," 1.

[276] Lewis, *Mining the Sky: Untold Riches from the Asteroids, Comets, and Planets*, 255.

[277] Lewis, 255.

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