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Asteroid Mining

A Review of Methods and Aspects

Vide Hellgren

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Department of
Physical Geography and Ecosystem Science
Lund University
Sölvegatan 12
S-223 62 Lund

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Asteroid Mining

A Review of Methods and Aspects

Vide Hellgren

Master thesis, 15 credits, in *title degree**

Supervisor:
Dan Metcalfe
Department of Physical Geography and Ecosystem Science
Lund University

Exam committee:
Abdulghani Hasan
Department of Physical Geography and Ecosystem Science
Lund University

ABSTRACT

According to many sources - such as television and science - the final frontier is space. And seemingly, one of the hottest related topics today are asteroids and their presumed promise of inherent wealth - or doom - depending on who reaches who first. The wealth is represented mainly by volatiles and water for fuel production and precious metals for technological development. The doom is represented by a possible impact from an asteroid.

This review has evaluated the main techniques and technologies being developed and tested to explore, prospect and harvest near-Earth asteroids estimated to be worth billions of dollars. Further, the two major space-related companies Planetary Resources and Deep Space Industries and their respective approaches to asteroid mining have been reviewed as well. Ultimately, the aspects of financial feasibility and environmental and legal issues have been approached.

It was found that a future space mission to harvest asteroids seems prosperous and even plausible in the near future if using a cost-effective mission architecture, perhaps even within a decade. The necessary knowledge increases quickly due to interests of profit and exploration and space is among the fastest growing businesses today. Theories on how to commercialize space were scrutinized to find negative effects to humanity and environment, though only a few were found – most side effects seem beneficial to the human race and the main ones are described in the text. And naturally, as the main themes of this thesis consist of future projects and their implications, much of the information herein is stated as estimations and speculations.

ABSTRACT (SWEDISH)

Enligt många källor – såsom television och vetenskap – är rymden mänsklighetens sista barriär. Och som det verkar är en av de hetaste rymdrelaterade ämnena idag asteroider och deras antydan till antingen rikedom eller undergång. Rikedomen representeras mestadels av flyktiga ämnen och vatten som kan användas till bränsleproduktion och dyrbara metaller för teknologisk utveckling. Undergången representeras av en möjlig kollision med en asteroid.

Denna recension har utvärderat de vanligaste teknikerna och teknologin som utvecklas och testas för att upptäcka, utvärdera och skörda jordnära asteroiders resurser med ett värde uppskattat till flera miljarder US dollar. Vidare så recenseras även tillvägagångssätten för de två största rymdföretagen Planetary Resources och Deep Space Industries. Slutligen så beskrivs även den finansiella genomförbarheten samt den miljömässiga och juridiska aspekten.

Resulterande information indikerar att ett framtida uppdrag för att skörda asteroider tycks kunna vara både möjligt och framgångsrikt om en kostnadseffektiv strategi används , möjligen till och med inom ett decennium. Den nödvändiga informationen ökar snabbt tack vare intressen för förtjänst och upptäckande, och rymdindustrin är en av dagens snabbast växande. Teorier om hur rymden kan kommersialiseras rannsakades för att finna negativa effekter på människor och miljö. Dock upptäcktes endast ett fåtal sådana – de flesta bieffekter, varav de största beskrivs i uppsatsen, verkar vara till nytta för mänskligheten. Det bör också uttryckas att eftersom de generella teman som utgör denna uppsats berör framtida projekt och deras implikationer, är delar av informationen som härmed framförs främst baserad på uppskattningar och spekulationer.

Abbrevations:

NEA- Near-Earth Asteroid
NEO - Near-Earth Object
AU - Astronomical Unit
PR - Planetary Resources
DSI - Deep Space Industries
IR - InfraRed
HS - HyperSpectral
UV - UltraViolet
VIS - Visible
NIR - Near-InfraRed
LEO - Lower Earth Orbit
PGM - Platinum Group Metals
NASA - National Aeronautics and Space Administration
ESA - European Space Agency
NEATM - Near-Earth Asteroid Thermal Model
TPM - ThermoPhysical Model
MIDI - Mid-Infrared Interferometric Instrument
VLTI - Very Large Telescope Interferometer
ESO - European Southern Observatory
KaBOOM -Ka Band Objects Observation and Monitoring
KISS - Keck Institute for Space Studies
NPV - Net Present Value
WISE - Wide-field Infrared Survey Explorer
UDMH - Unsymmetrical DiMethylHydrazine
ARM – Asteroid Redirect Mission

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INTRODUCTION

In a world of ever growing economy and technology, where populations grow with increasing demands, the resources found on our planet cannot be deemed infinite. Some of the Earth's key resources such as metals and minerals needed to develop technology and food industries could be depleted within 40-50 years according to Cohen (2007), based on known terrestrial reserves and growing consumption. The planet's resource account is growing empty and humans pollute its environment using fossil fuels; we are currently at 404 parts per million (PPM) of carbon dioxide (CO_2) in the atmosphere and 400 ocean zones are devoid of life (Dietz and O'Neill 2013; NOAA 2016). This estimation represents an additional incentive than mere profit to explore beyond earthly boundaries: for the continuation of our own and other species.

A future for the industrial and technological expansion of humanity requires future exploration, as well as new frontiers for this to occur (Badescu 2013). Since large parts of the Earth are already occupied with extraction of resources, one promising direction left for an exploration enterprise to head is up - into the vacuum and stillness of space.

The idea of asteroid mining has been proposed for a long time, however, it is not until recently that the technology and theories for such a mission are developed enough to be considered. It is asteroids, particularly the near-Earth asteroids (NEA), defined by Chamberlain (2001)asasteroids whose orbits have a perihelion (closest distance to Sun)less than or equal to 1.3 astronomical units (AU: distance Earth-Sun), which are the main goal for any possible future enterprise(Andrews et al. 2015). Even other near-Earth objects (NEO), such as comets, are possible targets for prospecting (Sanchez and McInnes 2012). They supposedly contain both the amount of volatile material and high-value minerals to make a trip there worthwhile. They also represent a reasonable incentive to colonize space (Taylor et al. 2008)

Also, Sonter (2006) explains asteroid mining as the key to the future economy of space. The asteroids are according to Sonter the most cost-effective way to commercialize space, and about 10% of NEAs are energetically more accessible than the Moon, meaning that less energy is needed to visit them.

The asteroids we know of are debris from the formation process of planets and a part of our solar system's history (Matter et al. 2011; Andreic 2016). Their sizes, shapes, bulk densities and surface properties are all clues to how and when they were formed through collisional evolution. The small asteroids have assumedly suffered less alteration through fewer collisions and have more conserved pristine material, which could be useful for a mining expedition.

These asteroidal collisions could possibly also affect Earth; the greatest risks to our existence could be the ones we are not anticipating, and Bostrom (2013) describes the issues surrounding risks of human extinction as poorly understood. Some NEA could one day be on collision course with Earth, and if that day comes, the knowledge and techniques to anticipate and deflect an asteroid should preferably already be developed, or the consequences could be fatal (Andreic 2016). An asteroid mining program could prove very beneficial for the research on collision prevention.

Two major companies, *Planetary Resources*(PR) and *Deep Space Industries*(DSI), are already planning to evaluate, prospect and harvest the resources of space (See http://www.planetaryresources.comand www.deepspaceindustries.com). These resources encompass metals, water and many other useful elements for development and construction both in space and on Earth. Both companies make believable claims on how they will achieve their goals. However, there are still many if's and how's regarding the current possibilities and technical challenges are more than likely awaiting anyone who dares venture into space for profit. It could therefore be of interest to describe and list the pro's and con's for the related material - to compare methods and company approaches and to provide any reader who wishes to indulge in an overview of one of the seemingly greatest and most promising enterprises of the near future.

AIM AND DELIMITATIONS

This review is made to provide the reader with a general understanding of what processes and theories are currently being developed, what methods are possible to use and combine and how sustainability and legal perspectives are applied to the space business in general.

Also, the feasibility and profitability of an asteroid mining program will be evaluated and discussed - to show the hypothetical benefits that space exploration can offer and to discuss possible side effects from a likely space prospecting mission. The main questions asked are:

- Can asteroid mining be done?
- Why will it be done?
- How will it be done?
- What general implications might it have?

With these questions in mind, the two major space companies Planetary Resources and Deep Space Industries will be compared and evaluated. This thesis will touch upon related space exploration programs and Earth mineralogy deficit issues - not elaborate extensively – to provide a context for the subject.

METHODS

The methodology in finding the information provided is through the reading of articles, journals, books and web-pages. When reading from company web pages, critical points of information are double-checked with independent scientific sources if possible.

RESULTS

REMOTE SENSING TECHNIQUES - DECIDING THE GEOLOGY OF ASTEROIDS

There has existed observational methods for the solar systems for many decades and even centuries. However, asteroids have long been an understudied celestial phenomena; there were no sufficient methods or technology around that would do the job properly. It was, according to Kowal (1996)not until almost 1970 when individual asteroids could be analyzed in a more specific matter, such as contour, size and composition through remote sensing techniques. Now the asteroids are, for instance, a major part in the unsolved mysteries about the origin of our solar system. And precise observations could be a way of solving them. Through observing asteroids using modern methods described in this chapter; information can be interpreted to gain knowledge of orbital position of an asteroid, the variation in texture of its surface, its shape and even rotation. By gaining information on these features and setting it into context with surrounding asteroids, it is possible to perform statistical analyses which could improve our knowledge of the asteroids evolution and origin in the solar system (Kowal 1996).

A very useful way of ascertaining the mineral composition of asteroids, is by comparing them to meteorites on Earth (Ross 2001). It is widely believed that these meteorites once came from the same asteroids now circling our solar system. From thorough analysis of the meteorites which landed on earth, combined with modern remote sensing techniques, we can be almost certain what minerals an asteroid does or does not contain. It is of utter importance to be as reassured as possible of these matters when taking the effort to actually venture into space to harvest minerals, since every moment is worth its time in investment cost. For this reason and other reasons, methods have matured significantly over the decades and are still being developed further.

According to (Harris and Drube 2014), there is both evidence and logical reasoning behind the correlation between the taxonomic type and composition of an asteroid and its density and porosity - C-type asteroids are less robust than siliceous S- and metallic M-types (see table 1). There are important variables to take into account when estimating the physics and thus the worth of any NEO, and these classifications simplify the generalization and documentation of asteroids. These are the main three types relevant for this thesis; however, there are other types and subtypes existing for other situations.

Asteroid Type	Chemical Composition	Resources	Additional Info
C-type (carbonaceous)	Clay and silicate rocks.	Water, other volatiles and carbonaceous compounds.	Most common. Furthest away from the sun; most ancient and preserved due to low temperatures. Some estimated to contain up to 22% water due to never reaching above 50°C. Other volatiles could be used for metallurgy, agriculture and air production.
S-type (siliceous)	Mostly stony materials (e.g. olivine, pyroxene) and nickel-iron metals.	Rocks, Nickel and Iron.	Existing mostly in the inner part of the Main Asteroid Belt and many NEO's belong to this type. Believed to be the source of the most commonly found *chondrite meteorite*.
M-type (metallic)	Primarily metal. Trace silicates.	Nickel, Iron, PGM's, Cobalt, Gold,	Also called X-type. Believed to be remnants from larger >100km asteroids, leaving only the extremely dense metal cores after massive collisions in the early days of the solar system. Found in the middle region of the Asteroid Belt.

Table 1. (Appelbaum 1993; PlanetaryResources 2016k)

These factors also have a significant influence on any hypothetical impact by asteroid on Earth, since it has been concluded that the structural robustness of impactors such as asteroids or meteorites strongly determines their fatality. Airbursts such as *Chelyabinsk* and *Tunguska* - where the latter actually knocked down trees over an area of 2000 km^2, even though it never reached the ground! (Kowal 1996)- are results of a more porous material whilst a more metallic body with similar size could reach the ground with devastating results, such as at *Barringer Crater* in Arizona (see fig. 1)(Harris and Drube 2014). Through high quality remote sensing combined with appropriate counter-measures, a disaster through impact of an asteroid could be avoided. This provides an additional reason to support the exploration of space and research of celestial bodies.

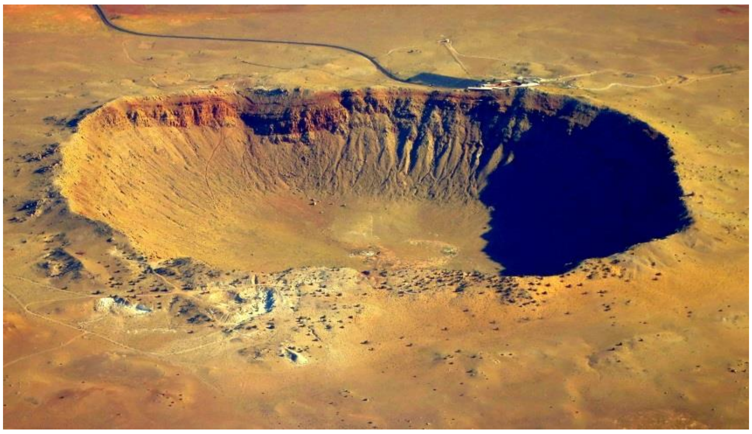

Figure1. Barringer Crater in Arizona, USA. Credit: Steve Jurvetson, Menlo Park.

Thus, remote sensing techniques with high accuracy are of high importance even for other reasons than economical or research related ones - they could one day, through precise observations, possibly help prevent a natural disaster of vast magnitude.

Several remote sensing methods are used independently or combined to pinpoint the asteroids most prone to contain valuable material. The most common techniques will be described in this study, from oldest and most basic to newer and more advanced. According to PlanetaryResources (2014), the optical telescopes decides spin rate and size, the radar determines the 3-dimensional shape and IR telescopes determines albedo and refines the type of asteroid. After that, the journey to explore and extract the minerals can begin.

SPECTROPHOTOMETRY

Photometry is a technique for simply measuring the brightness of an Asteroid (Kowal 1996). It is basically done through gathering light in a telescope, processing it through special filters and then capturing and recording the light. The observations are normalized through standard procedure to make precise comparisons possible. This is a relevant way of estimating an asteroid's physical composition, since they lack atmospheres which could affect the results with their own reflectance. In early stages, actual photographic and visual methods were used. These are in modern times replaced with electronic methods, such as a photoelectric photometer, which measure the light intensity of an object by applying its light emission onto a photosensitive cell(Warner 2007).The most recent technology is called Charge-Coupled Devices - more known as CCD cameras. These work through simultaneous comparison of the object of interest and several neighboring field stars as reference in a two-dimensional image. Various filters can be applied for analyzing different spectra of interest. If many filters are applied in succession to make an integrated result, the resulting spectral analysis is similar to that of *spectrophotometry*.

If the light reflected from an asteroid is measured at many wavelengths and subsequently compared with the color of sunlight, this can grant valuable information on what material the surface of the asteroid is composed of, which in turn is a strong indication of what the asteroid is generally composed of. The result is compared with reflectance from known types of rocks and minerals. These are the basic principles of spectrophotometry.

When deciding the composition of a rock, it is generally sufficient to determine the surface of it to make a qualified guess about the contents; at least if the rock composition seems fairly homogenous. Asteroids could also be heterogeneous in the chemical composition, making it more complex to estimate the core contents, which is important for financial reasons. Further, the way we perceive asteroids could be affected by various irradiation and collisional processes which may alter their surfaces (Appelbaum 1993). This is a problem for ordinary spectroscopy, which, however, could be mitigated with complementary thermal modeling (page 13).

RADIOMETRY

According to Kowal (1996)radiometry Is generally the technique for measuring infrared radiation from an asteroid. Just as when the Earth is struck by solar radiation, some is reflected and a larger portion is absorbed. The absorbed energy is emitted as long wave radiation which can be measured in the IR spectrum (see *fig 2*). The amount of reflected radiation is dependent on the asteroid's size and albedo. Hence, if the incident sunlight is known, comparing the emitted IR radiation with amount of sunlight reflected from the surface can give an estimation of the asteroid's albedo. When having determined the brightness, distance and albedo, and estimating the temperature distribution, the size of the asteroid might be computed.

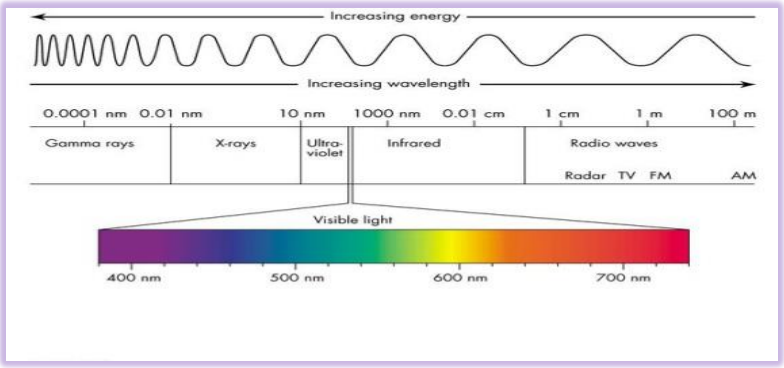

Figure 2. An image showing the different wavelengths of the electromagnetic spectrum. Radiometry is measured in the infrared part of the spectrum. Credit: www.cyberphysics.co.uk

However, some assumptions about the asteroid material must be made in advance, for this technique to be effective. This is due to the fact that the heat distribution differs between various types of asteroids, since for instance metal is a better heat conductor and heats up more uniformly. Even rotation rate of the asteroid matters, since the time the surface is in the shadows determines the coolness of the asteroid and thus the heat emission as well. The shape also contributes to certain variations in heat emission signatures. Nevertheless, these errors can in general be accounted and compensated for, giving a mere 10-15 % error when estimating the diameter of an asteroid, which has been controlled through polarimetry and direct observations during stellar occultations(Kowal 1996).

According to Hihara et al. (2015), using a thermal-IR imager and a near-IR spectrometer combined, it is possible to observe and estimate the geology and thermo-physical properties of an asteroid. Also the organic and hydrated materials could be detected.

SPECTROPOLARIMETRY

The most common methods for probing objects without atmosphere are reflectance and *polarimetry* measurements (Bagnulo et al. 2015). Wikipedia’s definition of polarized light is "the direction in which the electric field of an electromagnetic wave points" (Wikipedia 2016d).

Polarimetry measurements use a similar method as when looking at something through polarized sunglasses, then rotating the glasses to obtain different images of the object - depending on what material the object consists of, the image you perceive will vary.

The technique was first developed for individual asteroids in 1934 by Bernard Lyot, but took until the 1970s to be fully functional(Kowal 1996). The technique uses a polarizing material which rotates in front of a photometer, giving a measurement of amount and direction of polarization. These measurements depend on both mineralogy and texture of asteroid surface (metallic surface gives low polarization etc.), as well as the geometry of the situation: polarization is measured at different *phase angles,* which are the angles between Earth, asteroid and Sun. At zero degree angle, the asteroid is directly opposite the Sun from Earth.

It is - due to the angle requirement - therefore imperative to make observations during weeks or months to get sufficient data. It is then possible to plot amount of polarization against the phase angle to obtain a polarization curve (for example, see fig. 3).

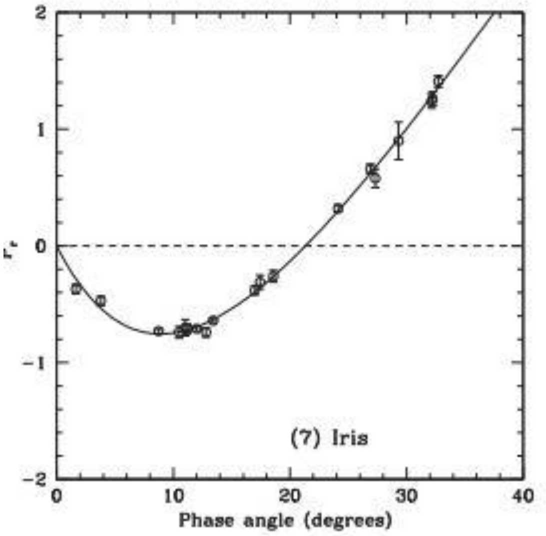

Figure 3. Curve of polarization for an S-type (silicate) asteroid named '7 Iris'. The parameters of interest in this curve are: depth of the negative portion, the slope of the positive branch and the phase angle where it changes from positive to negative. These variables correlate strongly with albedos and can be compared to lab measurements to estimate the observed material. Image adopted from Bagnulo et al. (2015).

Spectropolarimetry is polarimetry with many bands of wavelength taken into account, displaying the wavelength dependence of the linear polarization of the scattered light (Bagnulo et al. 2015). The usability of spectropolarimetric observations is still being tested, whereas to find out if its complementary information could show other characteristics which other methods miss. Bagnulo et al. (2015)conducted, according to their report, the first spectropolarimetric survey of asteroids of its kind. They show that objects displaying similar reflectance spectra may display totally different polarization spectra, suggesting both should be combined for best outcome of classification.

Even if in some cases it is contrasting what is expected from simple physical considerations, the fraction of linear polarization and the reflectance spectra may be positively correlated. This tells us that the observed materials are following similar surficial structures but they could differ in their chemical compositions. This could prove useful in future modeling of asteroid's surface structure.

It has been shown by Penttilä et al. (2005) that broadband linear polarimetry and spectroscopic can produce similar taxonomy of surficial chemical characteristics. It is suggested by Bagnulo et al. (2015) that spectropolarimetry could offer a more detailed complementation to spectrophotometry and should be investigated further.

HYPERSPECTRAL IMAGING

According to Chauhan et al. (2015)sampling of a spectral range of interest with a few broad channels only is the primary limiting factor of the multi-spectral sensor systems, which severely affects identification of mineral species and quantitative mineralogical assessment.
Hyperspectral imaging is similar to other electromagnetic observations, although it differs by using a vast amount of minor spectra - typically hundreds of narrow continuous spectral bands - resulting in more fine-tuned spectral reflectance data from the UV-VIS-NIR region. The goal of hyperspectral imaging is, according to Wikipedia (2016b), to "obtain the spectrum for each pixel in the image of a scene, with the purpose of finding objects, identifying materials, or detecting processes."
Hence, when using this method, information about every detail texture and composition can be extracted with high accuracy compared to the multispectral technique.

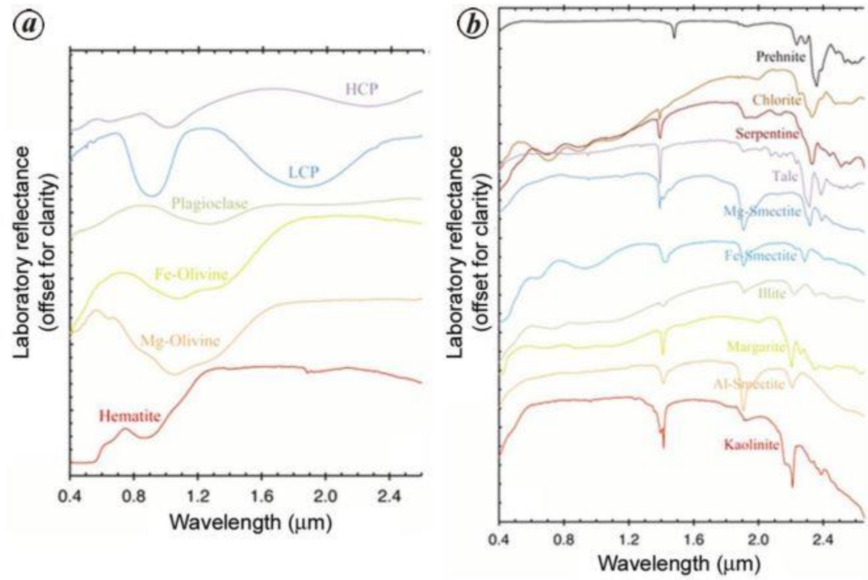

Figure 4. Example of reflectance spectra of (a) common rock forming minerals and (b) water-bearing minerals formed as alteration products on Mars. Figure adopted from Viviano-Beck et al. (2014).

If plotted against wavelength, the reflectance values show a *spectral reflectance curve* (see fig 4) (Chauhan et al. 2015). In this curve, certain transition metal ions, such as Fe^{2+}, Fe^{3+}, Mg^{2+} etc., are displayed as transitions in the NIR region (ca 0,7-2,6 μm) and silicates, salts and water bearing minerals are displayed in the mid- and thermal-infrared regions of the electromagnetic spectrum.
Even since hyperspectral imaging seems to be helpful when analyzing asteroid, to date (2015) no hyperspectral sensor has imaged any asteroid(Chauhan et al. 2015). However, this is exactly what PR is planning to do, which is described in the chapter *Space Shuttles and Technology* on page 17.

THERMAL MODELING

The heat signature of an unknown object in space can tell a lot about it. By measuring certain parameters through thermal imaging, useful information can be extracted from the analysis.

To obtain high-accuracy knowledge of near-Earth asteroids it has become common practice to use thermal models (Harris 1998). These models are normally based on IR observations from main-belt asteroids. However, since NEA tend to have more irregular shapes and are often observed at larger solar phase angles, the models have been empirically evaluated and modified for NEA's by Harris (1998).

This NEA Thermal Model (NEATM) is based on spherical geometry and can produce the diameter and albedo of practically any atmosphere-less body from thermal-IR data (Harris and Drube 2014). The model is an extension to the thermal model concept described by Lebofsky et al. (1986). The new model incorporates a fitting parameter (historically called beaming parameter) which takes both thermal inertia, spin vector, and surface roughness into account.

If the asteroid has a rough surface, the subsolar temperature is higher than expected with a smooth surface. This occurs due to the "beaming" effect, e.g. enhanced re-emission of light from surface elements that are facing the Sun (Harris and Drube 2014).This parameter of surface roughness could be modeled by adding hemispherical craters to the surface (Matter et al. 2012).

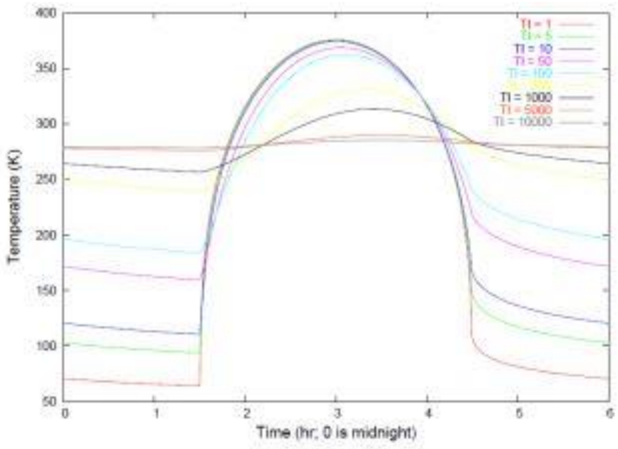

Figure 5. The thermal inertia: smoothing of the surface temperature distribution as a function of time. Different objects give different thermal inertia (TI) presented to the right. Image adopted from Matter et al. (2012).

Harris and Drube (2014) state that "the best-fit η value is a measure of the departure of an asteroid's temperature distribution from that of an object with a smooth surface and zero thermal inertia, or zero spin, in thermal equilibrium with insolation (in which case η = 1). " The best-fit η values from the NEATM could be used to estimate thermal inertia, where the calculation of Γ (thermal inertia) is based on the multiplication of thermal conductivity (c),density (ρ) and specific heat of the material (κ). Thermal inertia could be defined as a measure of the resistance of a material to a temperature, thus affecting the smoothing of the surface temperature distribution (see *fig 5*).It is inversely correlated to asteroid size (Matter et al. 2012).

Matter et al. (2011)have conducted the first thermophysical model (TPM) for analysis of interferometric (information from superimposed electromagnetic waves) observations of asteroids. Thermal IR data was obtained with the Mid-Infrared Interferometric Instrument (MIDI) and the Very Large Telescope Interferometer (VLTI) at the European Southern Observatory (ESO). The asteroid Daphne was used for analysis. The model they used was estimated to give a systematic uncertainty of 4 and 7% respectively, for the asteroid volume estimation, depending on variation of the technique used. The TPM analysis showed a surface thermal inertia derived to be smaller than 50 J m^{-2} $s^{-0.5}$ K^{-1} and moderate macroscopic surface roughness.

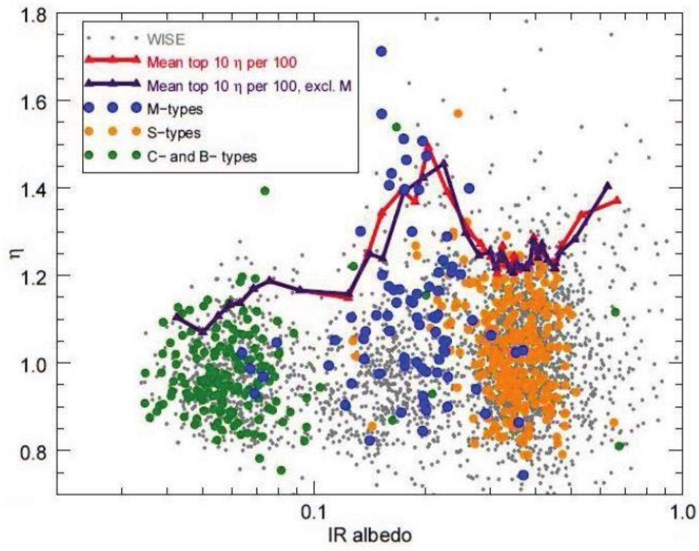

Fig 6. From WISE(Wide-field Infrared Survey Explorer(NASA 2015)) data. Points are η values versus infrared albedo for main-belt asteroids. Colored bullets represent taxonomy types. The red curve is a plot of the mean of the highest 10 η values in bins of 100 data points; the purple curve is the same excluding M types. Points with fractional uncertainties in η and IR exceeding 20% have been removed. Image adopted from Harris and Drube (2014).

If an asteroid has experienced metamorphism, aqueous alteration or melting, they will according to McSween Jr et al. (2002)differ in terms of thermal evolution. Their respective thermal signatures could be studied to learn more about the insulating effect of regolith (heterogeneous cover of rocks, dust etc. on top of solid rock), the buffering effect of ice and fluid flow and how heat distribution changes due to differentiation. A relationship between asteroidal peak temperature and heliocentric distance can also be calculated through thermal models. The usage of other heat sources than the Sun, such as electromagnetic induction and collisions, have been deemed sufficient enough only for simple calculations of plausibility. Furthermore, if a NEA shows signs of heterogeneity it could be analyzed through both spectral reflectance data and the NEATM to provide a fair estimation to whether the asteroid is only rich in resources on the surface or in the core as well. Harris and Drube (2014) also point out that possibly metal-rich candidates should be subjected to further optical, thermal-infrared and radar observations, as well as TPM to achieve the most precise estimations. However, to date(2014) no systematic study had yet been carried out of the potential of η, as derived by NEATM model fitting, as a tracer of metal content in asteroids(Harris and Drube 2014). An example of different η values compared to IR albedos of various asteroid types are presented in *figure 6*.

GROUND TRACKING

Tracking asteroids from ground level is also a possibility. According to Huddleston et al. (2014)there is at Kennedy Space Center, Florida U.S.A., a radar system being built as a technology demonstration which could be used for future tracking of deep-space objects such as asteroids. It is called the Ka Band Objects Observation and Monitoring (KaBOOM) and consists of a phased array of three 12 meter antennas (See *fig 7*).

Fig. 7. The KaBOOM site recently built at Kennedy Space Center. Source: NASA

According to NASA (2016), this project will "enable the implementation of a high resolution, high power Ka-Band radar system to better track and characterize (size, shape, spin, surface composition) Near Earth Objects (NEOs) like asteroids and comets, as well as, orbital debris. The ultimate goal of a future implemented radar system is to obtain images of NEOs to see details as small as 5 cm in size (about the size of a golf ball). Today, NASA's best radar images are limited to 400 cm (about the size of a bedroom)."

The idea is that the array can instantly compensate for any atmospheric twinkling due to its composition of three radar antennas. The radar will be functional during daytime, compensating for regular optical telescope's dysfunction during those hours. The KaBOOM array offers high range resolution (5 cm) and high spatial resolution (also 5 cm for orbital debris in geosynchronous orbit (GEO))

The transmissions in the Ka band (26–40 GHz, according to ESA (2013)) supposedly allow a wider bandwidth than the lower frequencies(Huddleston et al. 2014). However, the signal in these frequencies is far more susceptible to disturbances due to turbulence in the atmosphere or water vapor. The project is still being developed, and if is successful it will function as pathfinder for a larger and more precise device, which will be able to track and analyze objects of 15 m diameter up to 72 million km away. That is circa half the distance to the Sun and five times further than today's instruments are able to track (Huddleston et al. 2014).

VESTA - AN EXAMPLE OF ASTEROID ANALYSIS

A well-studied example of an asteroid is Vesta. It is an unusual and fascinating asteroid due to its composition, which has been studied even since the 1970's, being a differentiated body with basaltic crust exposed in a large impact crater which indicates volcanic or plutonic processes(Chauhan et al. 2015). It is also a massive asteroid - the third largest of the main belt asteroids - making it a suitable amount of material for a thorough study. NASA's Discovery Program was launched in 2007, and a part of it was Dawn, which is an exploring spacecraft sent out to investigate Vesta. Even though no hyperspectral sensor has imaged any asteroids, the spacecraft is equipped with multi-spectral sensors which have been used thoroughly to observe the geological nature of the asteroid.

Furthermore, the in situ exploration of Vesta has been a revelation to the interpretations of polarimetric measurements of asteroids through RS (Cellino et al. 2016). The asteroid is the only one known whose cyclic variation of the degree of linear polarization from reflected sunlight is synchronized with its own rotation. Supposedly, this variation derives from superficial heterogeneity in composition and albedo differences across the regions. This conclusion was at first more speculative and qualitative, however was later confirmed by Dawn's ground-based observations and the data is now more detailed; it could more or less be used as "ground truth" for future polarimetric measurements. The newly refined knowledge includes variations of polarimetric readings during rotations, various illumination conditions and the empirical relation between polarization and albedo - the latter is commonly used to derive albedo from atmosphere-less celestial bodies.

Another interesting finding with Vesta, is the probable link between itself and the Howardite-Eucrite-Diogenite suite of meteorites (NASA 2011a; Chauhan et al. 2015). This is suggested through analysis of the reflectance spectra of both entities respectively, and is a helpful clue to figure out the evolution of our solar system and reassuring the connection between asteroids and meteorites. Thus, it gives more 'ground truth' data to any asteroid mining enterprise, which maximizes the probability of making correct estimations regarding the contents of a targeted asteroid.

RESOURCE HARVESTING

The resources of the asteroids are the main goal of a hypothetical enterprise. The right NEA's could provide a multitude of resources in huge quantities (see *table 2* and *3*) (Erickson 2007). These resources will probably represent the backbone for future space explorations.

Volatiles	
Molecules	**Primary Use**
H_20, N_2, O_2	Life Support
H_2,O_2, CH_4, CH_3OH	Propellant
CO_2, NH_4OH, NH_3	Agriculture
H_2O_2	Oxidizer
SO_2	Refrigerator
CO, H_2S, $Ni(CO)_4$, $Fe(CO)_5$,H_2SO_4, SO_3	Metallurgy

Table 2. Useful volatiles obtainable from NEAs categorized by primary use. Based on spectral observations of whole asteroid population and chemical analysis of meteorites. Source: Ross (2001)

Metals and Semiconductors	
Element	**Primary Use**
Fe, Ni	Construction and manufacturing
Au, Pt, Pd, Os, Ir, Rh, Ru, Re, Ge	Precious metals for selling and technology
Si, Al, P, Ga, Ge, Cd, Cu, As, Se, In, Sb, Te	Semiconductors for industries (e.g. solar cells)

Table 3. Useful metals and semiconductors obtainable from NEAs categorized by primary use. Based on spectral observations of whole asteroid population and chemical analysis of meteorites. Source: Ross (2001)

Since the resources are the main objective, the means on how to retrieve them are critical. There needs to be a functioning plan on how to prospect, gather, process and deliver commodities. Using both PR and DSI as sources of planning, a mission architecture could assumedly look something as in *figure 8* below.

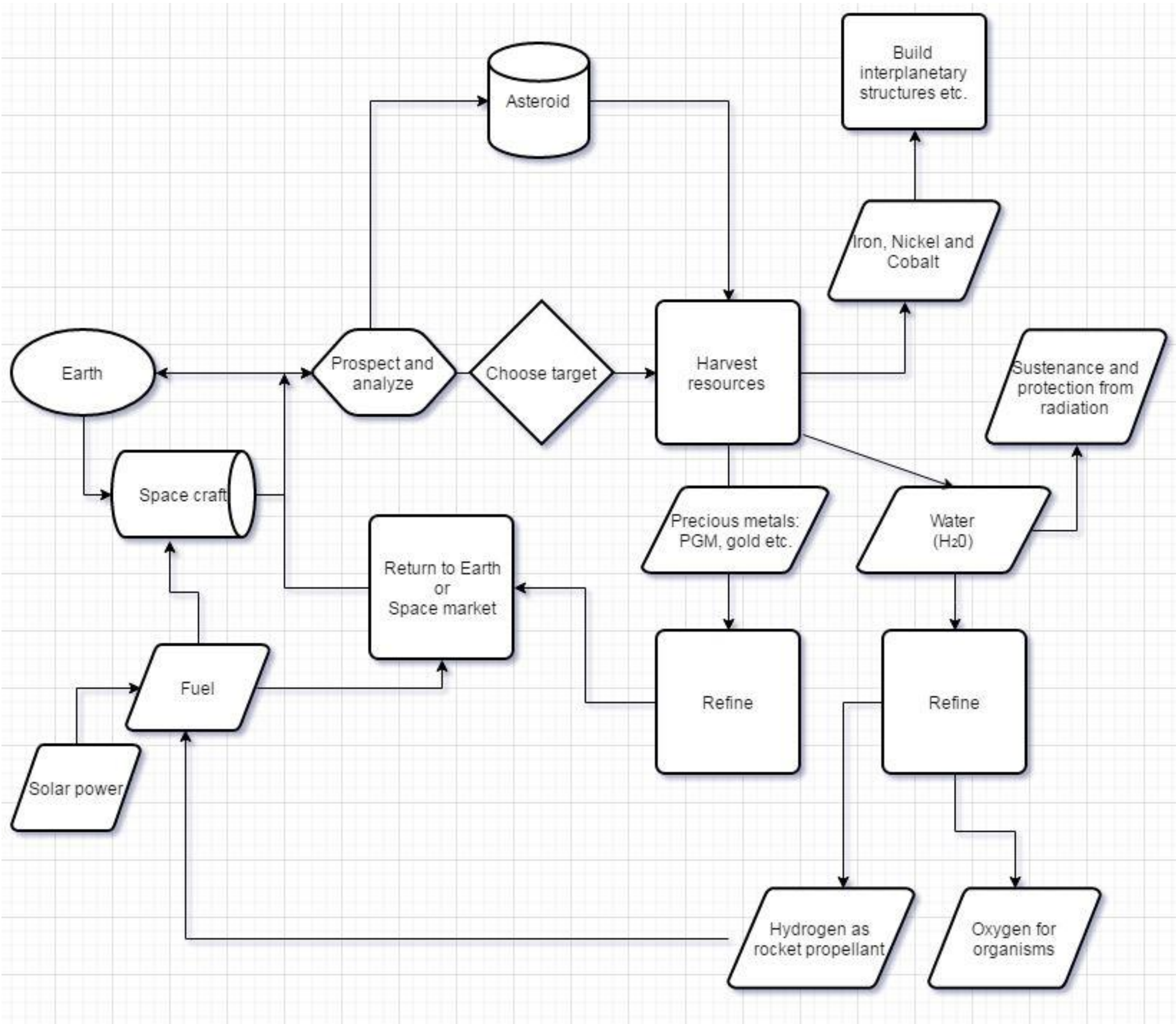

Figure 8. A flow chart displaying the main elements and processes included in a hypothetical asteroid harvesting mission. The procedure goes from Earth and back, excluding some minor steps and details. Based on information from PR, DSI, Ross (2001) and Andrews et al. (2015).

In a mission architecture proposed by Erickson (2007), a *command-control-communication* (CCC) unit orbits the NEA, controlling four minor harvester robots of which two acquire and process water and volatiles while two focus on metals. Thereafter a solar powered unit hydrolyzes water into H_2 and $O_2$and a solar-thermal propulsion unit returns any additional supply of valuable resources to LEO. The author puts emphasis on flexibility and enough critical units and fail-safes in order to carry out a successful mission.

Before the mining and extraction processes can take place, the harvesting spacecraft(s) needs anchoring and securing to the asteroid. This can according to Ross (2001) be done in several ways:

- Tie the spacecraft down with ropes around the NEA
- Drive in pitons – assuming the material is compatible
- Fire in harpoons or penetrators which resist extraction
- Screw in large area augers or screw-plates – assumes that there is a regolith and it is loose enough and compressible enough for a screw to penetrate
- Tie down into clasts of metal, ice, or solid silicate rock
- Use large area fluked anchors
- Burrow completely into the regolith (e.g. using contra-rotating screws)

METAL MINING

Figure 9. Illustration of how asteroid mining could look like. Adopted from AstronomySource (2012).

The technology needed to carry out the metal mining is still being developed. There are, however, a number of ideas on how to extract minerals in a zero gravity-environment – an illustration of how it could possibly look like can be seen in *figure 9* above. Many of the methods will be similar to the ones used on Earth: drilling, blasting, cutting and crushing (AstronomySource 2012). For instance, one idea is a device similar to a snow blower, anchored to the surface, which could be used to fire out loose rubble into space by using a spinning blade, collecting the material with a high-strength bag (AstronomySource 2012).

asteroid type	mining	processing
ice mixtures	blast, heat, distill	phase separation
friable rock	blast, rip	phase separation, mech, chem, mag
hard rock	blast, disc cutters	mech, chem, mag
metallic Ni-Fe (massive)	concurrent with processing	smelting, car-bonyl methods
hard rock-metallic Ni-Fe	blast, heat, rip	mech, chem, mag; smelting

Table 4. A table showing which mining situations could be related to which techniques. Adopted from Gertsch and Gertsch (2000).

Any method used is planned according to the physical properties of the targeted asteroid (see *table 4*). These will also be very dependent on pre-existing fracturing (Gertsch and Gertsch 2000). The extraction processes could require fuel in form of an either chemically or energy intensive matter - either through solar energy, working fluids, machinery or other fuels. An important detail is to use anything which exists locally in abundance, which is easy to access, as a cost-effective way to build up and develop the space mining capabilities without the need to return to Earth or LEO to restock on important tools and commodities.

This is correct for hypothetical building material as well, such as iron and nickel, to develop future space stations and colonies which could act as a gateway and relay between asteroid mining and Earth - for future transportation of valuable materials, accommodation etc.

NICKEL AND IRON

When conducting electrolysis of molten silicates, production of oxygen, iron and other alloys might occur (Appelbaum 1993). There is another method called *the Mond process* which could be used to extract nickel. Many techniques are being developed and considered and experimented with on meteorites on Earth (AstronomySource 2012).

There are theories on both how to extract valuables from asteroids on site, and also to bag whole asteroids to bring them into LEO, lunar-orbit or similar for further analysis and extraction (Gertsch and Gertsch 2000). NASA's Asteroid Redirect Mission concept (ARM) is planning to do exactly this; capturing a small asteroid and to return it to lunar orbit for both planetary defense and resources exploitation (Harris and Drube 2014).

If this would succeed, there is practically no limit to how much valuable metals a mission could bring home; the asteroid *16 Psyche,* one of the largest in the solar system, is believed to contain 1.7×10^{19} kg of nickel–iron, which could supply the world production requirement for several million years(Viateau 2000; Wikipedia 2016a).

Planetary Resources also claim that they are planning to use Iron, Nickel and Cobalt found in asteroids to build structures in space through 3D printing(PlanetaryResources 2016e). These structures would provide support to transportation and supplies for future space exploration. In January 7, 2016, PR published an article about the first 3D-printed object ever from asteroid metals (PlanetaryResources 2016i).

Sanchez and McInnes (2012) report that returning a substantial amount of asteroid resources to Earth's orbit could be a viable mean to provide support for future space ventures; building space crafts in orbit around Earth or similar would cut down much of the cost needed for lift-off through Earth's gravity field.

PLATINUM GROUP METALS

Planetary Resources explains Platinum Group Metals (PGMs) as some of the rarest and most usable metals on Earth (PlanetaryResources 2016g). They consist of ruthenium, rhodium, palladium, osmium, iridium, and platinum (see *fig 10*). This rarity is due to a lack of PGMs in the Earth's crust - they all gravitated towards the core in the early day of the planet. Consequently, all mines extracting platinum are situated near asteroid/meteorite impact or volcanic eruption zones.

Figure 10. A piece of pure Platinum metal. Credit: Financial Gazette.

The metals are also believed to be what is known as a sub-economic resource - namely what cupper was before electricity needed world-wide conduction, or oil before humans built a global transportation system based on it (DavinciInstitute 2014). It is, in other words, a resource of the future. It has some very fine physical characteristics and could revolutionize many high-tech industries and speed up research in many areas. PGMs could be used for the production of:

- Autocatalysts (for pollution control)
- Silicones
- Hard disks
- Electronic components
- Dental components
- Fuel cells
- Jewelry
- Medical supplies
- Petroleum
- Sensors

According to a precious metals management site (Matthey 2016). Even more uses exist.

One of Planetary Resources targets is an M-type asteroid, and may contain more platinum that has ever been mined on Earth to date (PlanetaryResources 2016k).The company gives this PGM comparison on their website:

"A single platinum-rich 500 meter wide asteroid contains about 174 times the yearly world output of platinum, and 1.5 times the known world-reserves of PGM. This amount is enough to fill a basketball court to four times the height of the rim. By contrast, all of the platinum group metals mined to date in history would not reach waist-high on that same basketball court."

(PlanetaryResources 2016h)

As a sign of economists starting to show interest for space resources, various examples could be made. For instance, recently (2015) a platinum-rich asteroid named "2011 UW-158" flew by Earth, with a value estimated to around 5.4 trillion dollars! It was circa 6 lunar distances from earth (2.4 million km) and could therefore have been a possible target if preparations had been made (Howell 2015).This produced articles in major newspapers such as The Independent (Sims 2015) and business magazines such as Business Insider UK (Orwig 2016).

WATER EXTRACTION

One of the most important resources in space is water. This is due to the fact that it could be processed into oxygen (O_2) and hydrogen (H_2) gas, where the latter is essential for use as a rocket propellant (LO_X/H_2) made from electrolysis (PlanetaryResources 2016d). There is already an established market for fuel in space, and extracting it from C-type asteroids could prove very rewarding. It will also expand travelling routes and serve as a sustainable fuel option.

Water could also prove useful as a *radiation shield* - if thick enough it protects any organic matter from cosmic radiation as well as the Earth's atmosphere.

One way to extract water is by heating an asteroid - partly or fully - and capture the vapor and distilling it, as in *fig. 11*. This could prove an easier task than first anticipated, due to space's unique physics.

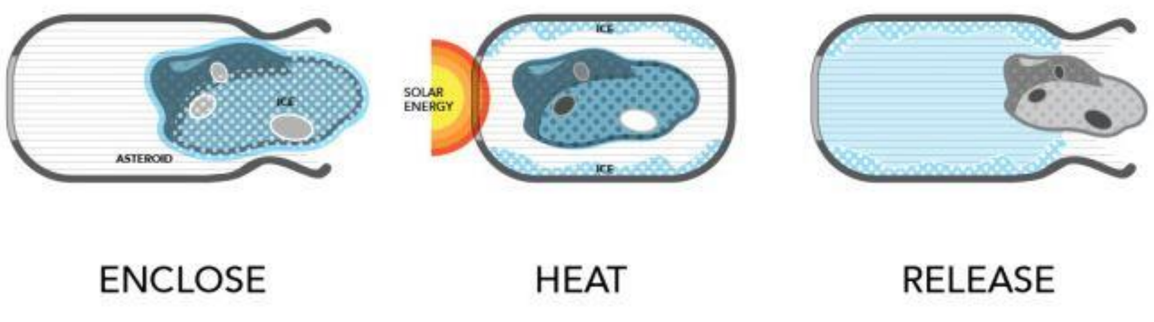

Figure 11. Illustration describing how PR are suggesting their extraction of water from asteroids would look like. Adopted from PlanetaryResources (2016d).

The vessel, with boundaries of low temperature, encloses a small asteroid or part of a large asteroid. It is thereafter heated by concentrated thermal energy from the sun and vaporized. When it reaches the walls, it solidifies instantly as ice. When enough water is captured, the vessel releases the asteroid to deliver its cargo where it is needed.

There already exists a large market for rocket fuel in space (PlanetaryResources 2016f), so the first resource to prospect will probably be water. This is due to the high cost of bringing water from Earth into space - every gram onboard could be counted in rocket fuel cost when defying gravity with machinery.

DeepSpaceIndustries (2016d)exclaim that their idea is to form specialized processing facilities in space, which can handle both asteroid regolith and volatiles, such as water and hydrocarbons, producing valuable products and oxygen for life support and propulsion. Also methane and methanol are potential rocket fuels which could be paired with liquid oxygen for a powerful rocket thruster. The space facilities will rendezvous with harvester and courier crafts for transportation of wares.

BIOTECHNOLOGY

On Earth today, biomining is used in approximately 20% of global copper and 5% of global gold production (Klas et al. 2015). It is defined as microbially based mineral extraction and is also related to biogas production, which is advancing globally. Analysis by Klas et al. (2015)suggests that production of biogas via methanogenesis could be done on C-type asteroids, resulting in hydrocarbon-based fuels. Biomining would be challenging under the hostile environment space provides, due to the risks for the microbes needed.

However, bacteria and archaea can inhabit the cold-desert soils of Antarctica, deep ocean subsurface fossil fuel deposits and acid mine drainages. There are so-called *extremophiles* which could even thrive during extreme physical and geochemical conditions. If the NASA-led Asteroid capture mission succeeds to put an asteroid into Earth or lunar orbit, further studies could be made on biomining capabilities.

This technology could prove a vital asset in currently proposed methods of extracting minerals and producing fuels on asteroids (Klas et al. 2015). It could increase both output and efficiency.

However, neither PR nor DSI are advertising for any related research or development on their respective websites in the present moment.

SPACE SHUTTLES & TECHNOLOGY

Space technology is under constant development. However, the approach on how to do it is also developing; to make research and development go even faster, it has even been proposed to make space technology *open innovation* (Johannsson et al. 2015). This is defined in the article as “the process of strategically managing the sharing of ideas and resources among entities to co-create value. Using an asteroid mining case study, the concept was shown to be promising for space technology development.

The mission architecture proposed by Erickson (2007) includes both AI-guided robotics and human tele-control to minimize risk and cost. In the same hypothetical mission, a larger unit is coordinating four minor vessels which could analyze and harvest the resources. The two major space endeavoring competitors, Planetary Resources and Deep Space Industries, have both developed similar strategies. They are developing their own versions of technology to explore, locate and harvest the asteroids chosen for exploitation.

Planetary Resources are, according to their website, developing three types of satellites to handle a future space mission (see *table 4*) (PlanetaryResources 2016j).The three series of space satellites will handle different levels of interface with space objects. The Arkyd Series 100 are deployed to orbit Earth in the LEO. The Arkyd Series 200 would intercept NEOs to analyze and take minor samples. The Arkyd Series 300 are the most capable and deep-going of the PR space crafts. Although they all are built differently and are developed for separate types of missions, they have one main thing in common: they all depend on the *Ceres Sensor* for acquisition of correct data about their environment and potential threats and prospecting targets.

The Ceres Sensor is a combination of mid-wave IR and visible to near-IR hyperspectral (HS) imaging telescope (see example in *fig. 12*). During the prospecting phase, the sensors for both visible and non-visible spectra are used to acquire an asteroid's composition and characteristics, and consequently its value. This data is complementary improvement to data collected from Earth (PlanetaryResources 2016j).

Figure 12. Depiction of hyperspectral imaging, such as is used by the Ceres Sensor. Credit: Dr. Nichlas M. Short, Sr. at NASA.

Planetary Resources are using beta-versions of their Arkyd series to prove their functionality and trustiness before sending them out on actual missions, adapting and learning from any mishaps which could occur in the experimental phase. Their first space crafts to demonstrate the technology are the Arkyd 3 (on orbit since July 2015) and Arkyd 6 (launches summer of 2016).

Also, they are deploying a constellation of 10 minor satellites of type Arkyd 100 (see *fig. 13*), into LEO to deliver information to already existing markets for space and Earth (See page 31 for more information on environmental monitoring from space). The constellation is called the *Ceres Constellation*.

The Ceres Constellation is providing weekly IR and HS data for any spot on Earth at lower cost than any existing multispectral data, according to PR. It could also be re-programmed in orbit to "search for and identify specific materials and temperature signatures" and is accordingly the first of its kind with this capability. The Ceres system is supposedly very adaptable and customizable for many possible situations. (PlanetaryResources 2016c) However, the sensors are still in early stages and could experience errors. For instance, between February 18-24 2016, NASA reports that the "Ceres Terra" was dealing with an anomaly causing all systems to go into "safe mode"(Loeb 2016). Luckily, the issue was resolved quickly.

Figure 13.The Arkyd 100 satellite. Credit: Planetary Resources.

DEEP SPACE INDUSTRIES are developing their own technology based on what they call the "The Mothership Carrier Craft". The latter contains the smaller *nanosats* (mini-space crafts) on the journey to the destination. While doing so it supposedly protects them from radiation and thermal concerns. The Mothership is also providing propulsion, communications, power and data, has flexible volumetric accommodations and acts as high bandwith communication relay. Data from spectral imaging etc. is being relayed back to Earth for asteroidal analysis.

Planetary Resources	**Description**	**Deep Space Industries**	**Description**
Arkyd Series 100: *TheLeo Space Telescope*	This is an instrument used to find and analyze what resources are available on NEA. It is less costly than other alternatives.	Cubesats*: Fireflies*	Fireflies are triplets about the size of a briefcase (15 cm wide) and they examine separate asteroids. They can "hitchhike" with a larger rocket during one-way trips lasting between 6 and 24 months depending on target.
Arkyd Series 200: *The Interceptor*	As the name implies, this satellite would land on the asteroid to make a more concrete analysis of the available resources.	Cubesats*: DragonFlies*	These spacecrafts are a bit larger than FireFliesand are also deployed three and three. They gather small samples (5-10kg) and return them to Earth.
Arkyd Series 300: *Rendezvous Prospector*	This satellite would research and find resources deeper into space. The highest evolved of the spacecrafts.	Single craft*: Harvestors*	Harvestors are the largest crafts and they venture to asteroids and gather rocks and regolith and return to high Earth orbit for processing.

Table 5. Information about space hardware gathered from both companies. (DeepSpaceIndustries 2016c; PlanetaryResources 2016j)

Furthermore, DSI calls their advances in technology "C3PO"-technology: Communications, Propulsion, Pointing, Power and Operations. They claim these advances allow the company to utilize existing *CubeSat* architecture and combine it with their own unique technology(DeepSpaceIndustries 2016e).

Cubesats are the results of developing very small satellite technology for space exploration etc. The first version came out at least one decade ago, according to Ernst (2013), and made a strong impression on the space market - resulting in a diverse variety of related products (Toorian et al. 2008; Selva and Krejci 2012).
According to Planet Labs (Marshall and Boshuizen 2013), there is now even an upcoming paradigm shift in LEO activities, resulting in a higher amount of smaller space crafts rather than large, "clumsy" single space crafts, and DSI is taking this technology into deep space.
One of the upsides are the possibility to scan from several perspectives simultaneously. Further, any failures of one single satellite would not be fatal to the mission at hand, due to backup nanosats. Cubesats have technology based on both large deployable solar arrays, minor Nitrogen or water-based thrusters and even an engine fueled by Hydrazine (Ernst 2013).The developed technology combined with the in-process hardware, such as ion or plasma engines being developed, would allow an equipped space craft to commit a wide range of useful activities.

When harvesting, DSI's Harvestors will be built for multiple journeys. They will bring thousands of tons of material rather than whole asteroids, since they claim it could be a risk for Earth if anything would malfunction on the way back. The Harvestors will use higher power solar arrays to drive high-efficiency ion thrusters(DeepSpaceIndustries 2016b).

DSI have also developed the *Comet-1 Water Thruster*. It is a "low-power, low-profile, high total impulse electrothermalmicropropulsion system that uses water as propellant" (DeepSpaceIndustries 2016a).
The Comet-1 is compatible with Cubesat technology but is suitable for a wider variety of space crafts and is very polyvalent. It has an unpressurized system during launch, a digital command and telemetry interface and uses a non-toxic propellant (from water).

TARGETING ASTEROIDS

ASTEROID AVAILABILITY

While the population of asteroids in our solar system is estimated to exceed 60 million, we only have knowledge about circa one percent of these(PlanetaryResources 2014). We discover about 3 new every day, according to Planetary Resources. The ones which are in the vicinity of our planet, referred to as NEOs or NEAs, have a huge population as well, and around 20 000 have a diameter larger than 100m (see *fig. 14*) (Elvis 2013). However, only a few would be profitable to prospect. The few asteroids actual for an upcoming space mission are chosen due to many variables; firstly, remote sensing techniques described earlier are applied; physical variables of the object and other relevant circumstances are considered to calculate the most reasonable asteroids to approach.

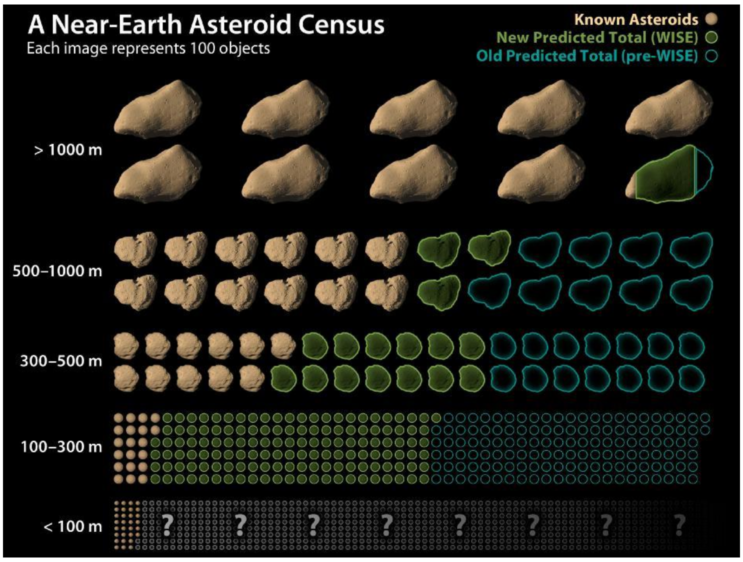

Figure 14. A visualization of the size distribution of NEAs in the solar system, before and after WISE(NASA 2011b). NOTE: Since this information is constantly updated, this image is only for comparative purposes. Image adopted from: NASA/Caltech.

HOW TO TARGET THE RIGHT ASTEROID

When newly discovered asteroids are being evaluated from Earth or satellite, there are a few physical variables to consider when choosing target asteroid. These are gathered from O'Keefe (2016)at PR's website and put into *table 5* below.

Delta V	Also known as the "speed limit of space". Basically a measurement of energy needed, calculated through the Tsiolkovsky rocket equation (NASA 2012), to travel between two physical bodies. A lower Delta-V - preferably below 5 km/s - allows less energy loss during transportation, thus allowing for more tools instead of fuel onboard.
Spin rate	Assumedly occurs due to a former collision. A high spin rate complicates any interaction with the asteroid, and it is hence not recommended to prospect it. However, most asteroids large enough to be targeted do not spin so fast.

Size	Planetary Resources targets are typically circa 300 meters in diameter. This is to ensure a profitable amount of ore or water.
Orbit	How the asteroid is orbiting in the solar system is of high importance, since it determines when and how often it passes by Earth. An inclined orbit, with an angle from Earth's orbit, makes a mission to it very implausible even if all else matches the criteria.
Type	As a result from the advanced remote sensing techniques, the type and composition could be determined. The first targets of PR are C-type asteroids containing up to 20% water. Future targets will be M-type asteroid.

Table 5. Variables to take into account when choosing asteroid for harvest. Source: (PlanetaryResources 2016e).

Sanchez and McInnes (2012) show that the utilization of asteroid resources may well be more viable than for instance the Moon's, since the Moon requires more energy to evade after resource pick-up. Their report is based on a statistical population of NEA, where the Delta-V has been taken into consideration to approximate the amount of asteroid resources within a given specific transfer energy. The resulting conclusion was that large asteroids with lower transfer energies are recommended. It was also concluded in the same report that the size distribution of NEO ensures that the most of the exploitable mass is made up by the larger objects close to Earth. Thus, a lot of exploitable mass could be harvested through only a few mining or capture missions. They suggest to search for objects between tens to some hundreds of meters in diameter with orbits giving a low transfer energy requirement.

Furthermore, techniques to find the most promising NEA's in terms of value are depending on the remote sensing methods described earlier in this study. Harris and Drube (2014) describe the pinpointing of a metal-rich asteroid to be complicated using only reflectance spectroscopy. Nonetheless, the use of the aforementioned NEATM and its fitting parameter, η, derived from WISE taxonomy and radar data, is claimed to be a useful indicator to finding valuable metallic asteroids. The authors have identified 18 such asteroids based on their η-values and suggest further optical complementary analysis.

FINANCIAL FEASIBILITY

Investing in space enterprises could be seen as a great risk, especially when so much is still unknown and is being researched in this very moment. Nevertheless, when modern "gold rushes" occur, they presumably do not happen on safe ground with known factors and resources – they happen on new and partly unknown areas with some degree of risk included, like with the avalanche-like expansion of the internet and related businesses(InternetWorldStats 2016). However, the space business is a serious one with ambitious people and plans; Planetary Resources, for instance, is backed by people such as Google executives Larry Page and Eric Schmidt, filmmaker James Cameron and Charles Simonyi, an early manager at Microsoft Corp. and now CEO at Intentional Software (PlanetaryResources 2016b).

So why are these famous innovators and investors interested in asteroid mining opportunities? The answer is simple: It could be very profitable. The vastness of space offers unparalleled economic opportunities and the technology has now matured enough to make it possible to act.

Entrepreneurs with fortunes from the last "gold rush" - the computer and internet revolutions - are now investing in space, according to Erickson (2006). The possibility for civilians to afford space travels in the near future is attracting many investors, and combined with new ideas of marketing, such as crowd-funding, as PR did while offering a photo of yourself taken by the first publicly accessible space telescope (Kickstarter 2015), and the open source concept suggested by Johannsson et al. (2015), the whole enterprise is a public affair where anyone could invest and be a part of humanity's next possible paradigm shift. In March 2016 Eric Anderson, co-founder and co-chairman of PR, said to CNBC that they are planning to have their first mining mission within 10 years (Ioannou 2016). For people to invest, however, a high level of feasibility and estimated profitability is important.

When considering feasibility of a space mission, what counts is mostly the cost versus the benefits or profits. Also, the technicalities must be sufficient to assure some degree of certainty of success.

Lee (2012)states six economic variables factoring into the feasibility:

- Research and development costs
- Exploration and prospecting costs
- Construction and infrastructure development costs
- Operational and engineering costs
- Environmental costs
- Time cost

These costs will need careful attention to perform a successful mining operation. Furthermore, the knowledge to target the right asteroids is also imperative – in *table 6* below are the 5 top most cost-effective asteroids according to the scientific asteroid database *Asterank*.

Asteroid	**Est. value**	**Est. Profit**	**Δv (km/s)**	**Resources**
Ryugu	95 billion	35 billion	4.663	Nickel, iron, cobalt, water, nitrogen, hydrogen, ammonia
1989 ML	14 billion	4 billion	4.888	Nickel, iron, cobalt
Nereus	5 billion	1 billion	4.986	Nickel, iron, cobalt
Didymos	84 billion	22 billion	5.162	Nickel, iron, cobalt
2011 UW158	8 billion	2 billion	5.187	Platinum, nickel, iron, cobalt

Table 6. Above are the five most cost-effective asteroid targets listed, provided by information from Asterank which is a scientific and economic database of over 600'000 asteroids(Asterank 2016).

However, PR have other asteroids in mind for initial prospecting and harvesting; mainly C-types to harvest for water and other volatiles. The asteroid names on their list are:

2014 EK24, 2014 SC324, 2013 PA7, 2011 CG2, 2008 HU4, 2002 TC70, 2001 QC34 and*1999 JU3.* They are all based in Aten, Amor and Apollo orbits around the Sun (see *fig. 15*).

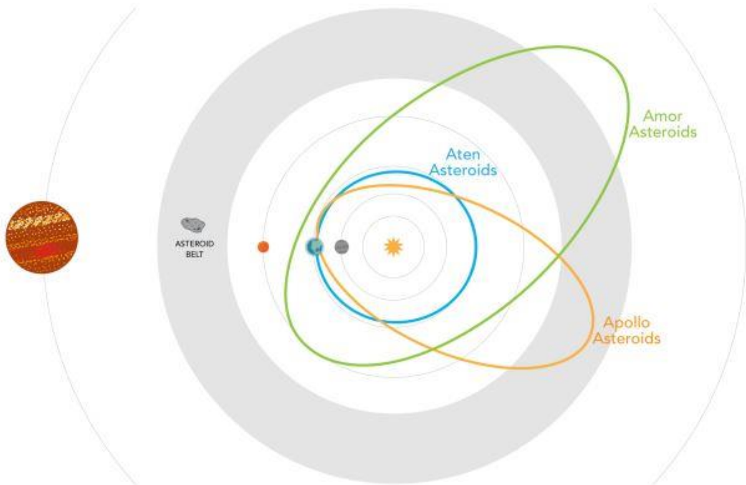

Figure 15. Image describing the three common orbit types where PR have found their targeted NEA's: Amor, Aten and Apollo orbits.

The Keck Institute for Space Studies (KISS) made a feasibility study on an *asteroid capture-and-return-mission* published in April 24, 2012(David 2012). The focus was put on the relevant technology and the details in moving a NEA weighing about 500 tons and 7 meters in diameter, setting it into lunar orbit by year 2025. The positioning in orbit around the moon would prove a good spot to venture out from Earth to analyze and experiment further, to improve our knowledge and research in the matter. It could also stimulate multinational cooperation in space when using the orbiting asteroid as a meeting point to learn how to sample and process asteroid material. The study gave a positive result on feasibility using the technology present and developed during the time written. However, the total cost is estimated to be 2.6 billion US dollars.

According to the economy site Investing News, one of the co-founders of PR, Peter Diamandis, said in 2012 that a 30 meter asteroid can hold between 25 to 50 billion dollars' worth of platinum at today's prices(Kumar 2012). *The Economist* also wrote that research has been made that implies a capitalization of at least 100 billion dollars would be necessary for an asteroid mining-venture to succeed(Economist 2012). This estimation is shared with Ross (2001)as well.

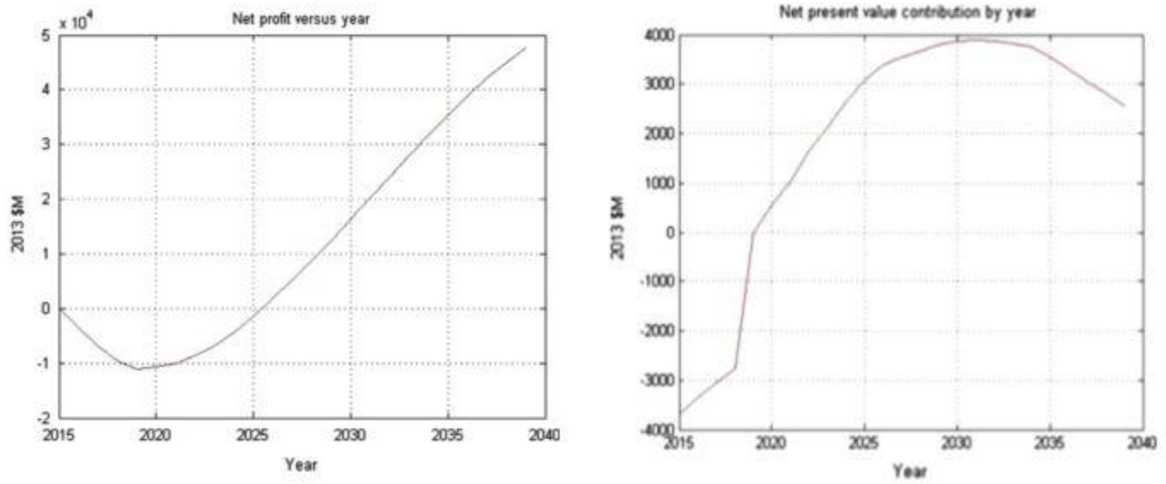

Figure15 represents estimated net profit per year after initialization of enterprise and figure16 represents NPV estimation per year. Figures adopted from Andrews et al. (2015)

Andrews et al. (2015) show that there is a possibility to make outstanding profits, if the approach is well thought out and appropriately financed (see *fig. 15* and *16*) . They also point out that, using commercial costing data, which run approximately 30-40% of NASA costing guidelines, they calculated a 35% Net Present Value (NPV, a measurement for profitability by subtracting outflow from inflow of cash(Ross 2001; Wikipedia 2016c))over 20 years.

Ross (2001) states that the economics of the project is mainly driven by mission velocity requirements, by the propulsion system type (depending on fuel availability and cost), and by project time duration and cost-per-time. Also, NPV is the correct figure of merit for evaluating feasibility of space mining ventures.

The expected NPV is, according to Ross (2001), a function of:

- The Delta-V required for return and capture into LEO combined with exhaust velocity of the propulsion system (together determining propellant use)
- The efficiency of the remote miner (kg output per day per kg of equipment mass)
- The duration of the mission cycle
- The value of the product being delivered into LEO and the current market interest rate

Erickson (2007) emphasizes that an "efficient, flexible and cost-effective mission utilizing adaptable and resilient robotic components is essential to establish NEA mining as a commercial enterprise". In the proposed mission architecture, the potential problems highlighted are:

- Failure of components
- Varying surface conditions and mineralogic content
- Fluctuating solar exposure (due to asteroid rotation) and its impact on solar power units
- Extreme temperature changes
- Drilling in milli-gravity conditions
- Handling of regolith dust
- Managing liquid H_2

One estimation was made in the late 1990's that the primary target for mining would be a 1 km M-type asteroid in the 90^{th} percentile of iridium richness, due to the high containment of semiconductors in this type (Kargel 1997). It was assumed that the harvested semiconductors placed into LEO would acquire the value 'p' estimated by:
$p = p' + C_{orbit}$
where p' is the cost of these materials from terrestrial sources and $C_{orbit}$is the launch cost to LEO per kg. The idea is thereafter to manufacture photovoltaics directly in LEO to be insensitive to launch costs.
As described by Ross (2001), the semiconductors would give the largest financial profits if there was a large-scale space solar power industry. As for now in 2016, PR and DSI have deemed PGM and water the main and most profitable resources, but the demand for semiconductors may well be rising with the need for globally sustainable energy.

Andrews et al. (2015)predicted that with a large enough initial investment (equal to that for the US North Slope Oil Field), the global yearly supply of PGMs could be increased by 50% and around 1500 tons of hydrogen-based propellant/year would be available in LEO. Also, solar panels could be assembled at low cost in orbit around Earth. The initial investment would have a discounted NPV return of 22% over twenty years.

Conclusively ,the space industry is already among the fastest growing industries today(Dempsey 2016).Its current revenues exceed about 250 billion dollars per year, though much of this is connected to military defenses, communications, and weather and environment monitoring (see page 32). The space industry growth will, according to Dempsey, mirror the global economy of the future.

SUSTAINABILITY & SIDE EFFECTS

EXISTING EARTHLY MINING ISSUES

Nansai et al. (2015) have conducted a mining risk assessment for Japan regarding what they call "critical metals" - which implies metals essential for future technologies but with limited access due to few countries with mining possibility. These include cobalt, neodynium and platinum. The industries for similar material grow as a consequence of low-carbon emission policies worldwide, where many low-carbon energy technologies use critical metals to function. The side-effects of mining, processing, recycling and disposing of these metals have many risks, including environmental hazards and public health issues(MIT 2016). However, even though the study was performed in Japan, this is not a mere national issue - the study suggests it is always affecting other nations and is considered a global issue.
The study concludes that Japan is incurring a high mining risk, especially because its use of neodynium, and that countries which apply low-carbon technologies should be aware of the risks included with metal mining of critical metals.

Earthly mined critical metals also represent a possible conflict factor in countries such as Kongo and South Africa (Ayers 2013; Carpintero et al. 2016). Here, the valuable resources could be used to buy weapons and to continue conflicts, as well as invite to the interference from foreign powers which could take advantage of the situation. This is mainly due to the scarcity and economical value of the resources, as the situation is today. For instance, the high-value mineral Coltan is sometimes by media called the "blood diamonds of the 21st century"(Nwoobserver 2013) and are a source of many conflicts and funding of militias, rebels etc. (Melcher et al. 2008). This particular resource is just brought up as an example and is not claimed to be relevant in asteroid mining per se.

Andrews et al. (2015) state that currently 81% of the world's primary energy is based on fossil fuels.
In 2010, only 2% of the world's energy consumption was provided by non-hydroelectric renewables. The problem to change this lies within the cost and risk; many key technologies are relying on critical metals and are either too expensive, unproven or scarce on the planet. A larger supply of critical metals would probably help mitigate the problem. It is also reasonable that these mining-related issues could reach some level of relief due to other, remote, sources of the critical metals.

SIDE EFFECTS

In the book "Harvesting Space for a Greener Earth" by Matloff et al. (2014), several strong arguments are made for doing exactly what the title implies - harvest space for a greener Earth.

Here follow the main arguments for the enhancement of human life through space exploration:

1. **Raw materials from space**: As shown in the RS section (page 8), there are many useful resources abundant in space, and especially in asteroids. Certainly, other celestial bodies have resources as well, as the authors point out, "the Moon's mass is about 44 % oxygen, 19 % magnesium, 6 % aluminum, 20 %silicon, 7 % calcium, and 3 % iron, with trace amounts of other elements" (Matloff et al. 2014). However, as mentioned before, the NEAs remain the "low hanging fruits of the solar system" (quote: PlanetaryResources (2016a)) due to their unique physical features with almost zero gravity and no atmosphere, as well as their valuable compositions.

2. **Power from the Sun**: The authors point out the fact of a virtually infinite supply of clean energy in form of sunlight - we just need to invest and venture out to harness it. From the tremendous amount of power from the Sun, $3.86*10^{26}$ W, circa$1.74*10^{17}$ W - or 1.368 W/m^2 - reaches the Earth. To compare this, the human race's total power output 2005 was circa 1.5*10^13 W. It is a mere 0.009% of what the Sun puts out every second. Furthermore, on Earth a typical solar power plant will receive about 100 W/m^2, when factoring in all disadvantages such as clouds and day/night cycle, while a similar power plant in orbit would receive about 1.400 W/m^2.

3. **Environmental monitoring from space**: There are many environmental phenomena that could be monitored from space in a highly useful and effective fashion. Main examples are: Climate change (spring leaves arrive 5 days earlier in Northern Europe since 2008)

- biodiversity and transgenic crop monitoring
- changes in measurements
- atmospheric temperature
- desertification and
- natural disasters .
- sea levels (see *fig. 17*)
- global ice

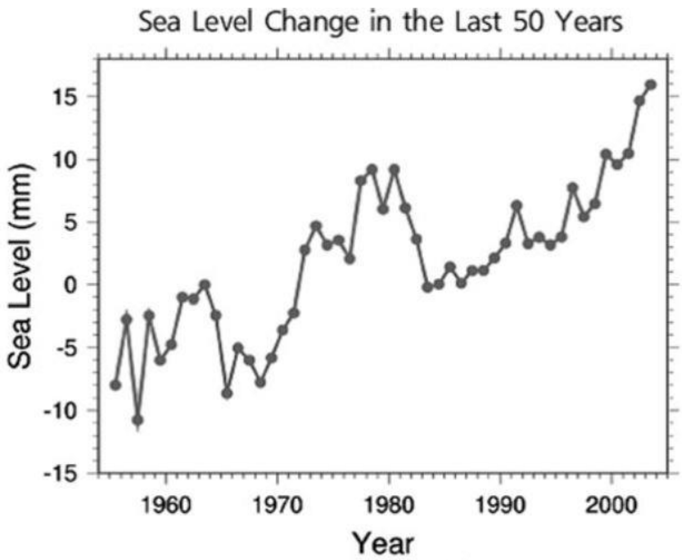

Fig 17. Global sea level monitored from space. Adopted from Antonov et al. (2005)

For environmental monitoring from space, Planetary Resources uses their *Ceres constellation* equipped with both mid-wave IR and hyperspectral imaging (PlanetaryResources 2016c). These functions are capable of producing following

- Night-imaging capabilities (IR)
- Temperature mapping (IR)
- Water content measurement (IR)
- Spectral fingerprinting (HS)
- Material identification (HS)
- Plant phenotyping (HS)

4**. Protecting Earth**: In an article by Bostrom (2013)addressing existential risks for our planet and its population, a hypothetical asteroid impact is mentioned as a significant, though amendable, danger to our very existence. Since the air burst over Siberia 2013 which injured about 1.500 people (Matloff et al. 2014)), the interest for anticipating threatening NEOs awoke anew. To protect the planet, it would be practical to track, categorize, investigate and develop techniques to divert the trajectories of NEOs threatening Earth. One such technique is sending a robotic spacecraft, which gradually changes its orbit to oppose the direction of Earth and most NEOs, its relative velocity to the Earth-threatening NEO would be approximately 60 km/s. The resulting collision could alter the NEOs route towards Earth and divert a catastrophe, if sent out in time and with high precision. Exploring and colonizing space would most likely contribute in the development of similar planetary defenses against any future asteroidal threat.

Harris and Drube (2014) suggest that a threatening NEO is probably robust and massive, possibly an M-type with a high concentration of metal. Confirmation of composition through thorough RS analysis would be recommendable, especially using NEATM with η fitting from WISE data, since mere reflectance spectroscopy can not specify the core components with certainty. The resulting data would be critical for any deflection-mission planners to manage any mitigation or evacuation depending on situation.

There is also the risk for self-induced impact with an asteroid. This could happen if, for instance, during NASA's Asteroid Redirect Mission something would malfunction and the asteroid would not be able to break properly before reaching Earth as a result. However, DSI writes that the company collects loose soil and rocks instead of whole asteroids so that they pose no risk to people on Earth (DeepSpaceIndustries 2016b). PR are currently not planning to bag whole asteroids either.

5. **Mitigating global warming using planetary engineering**: There are many ideas on how to lower global warming through geo-engineering. Some examples from the book(Matloff et al. 2014):

- *Volcano simulation* -the release of artificial aerosols in the stratosphere, increasing the albedo.
- *Local reforestation* and *artificial phytoplankton blooms* - causing the global Co2 amounts to decrease.
- *Increasing Earth's reflectivity* - The authors mention a scientific paper recommending the public to paint their rooftops white! If this policy was generally accepted, the result could cause the Earth's albedo to lower to an CO2 emission reduction equivalent of 25-150 billion tons.

These theories seem very Earth-based but actually have much to do with space development since they should be aided by well-planned monitoring from above. Planetary Resources are doing exactly that with their Ceres constellation which is a result of research for mainly asteroid mining(PlanetaryResources 2016c). However, these global experiments could be difficult to anticipate and stop in time if they result in a positive feedback loop, causing a new ice age instead. Hence, a space-based approach without that issue is presented in the next step.

6. **Mitigating global warming using space-based approaches**: The main suggestion here is to "utilize mined asteroid material to create a huge, stationary sunshade in space" (Matloff et al. 2014). If these "sunglasses of Earth" are properly designed and positioned, the resulting shade could reduce the solar energy incident on Earth, presumably enough to alleviate global warming. The device would be positioned at the L1 point in space for optimal performance and stability (see fig. 18). Another upside with this version of space-based geo-engineering is the possibility to move or modify the structure if the resulting global cooling seemed too rapid. Controlling the process is essential when experimenting with global net insolation. Hence, we could avoid the risk of an anthropogenic induced ice age, which was the problem with the aforementioned geo-engineering methods.

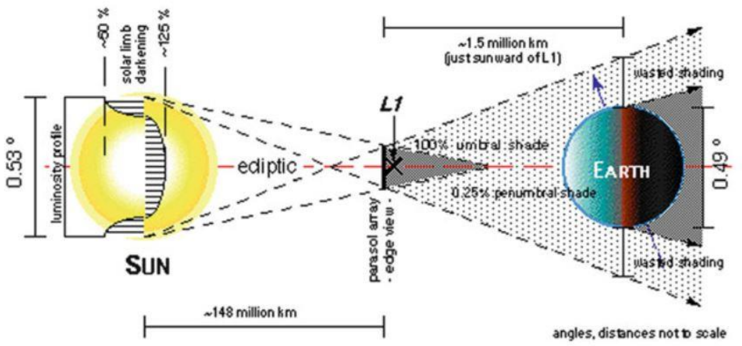

Figure 18. The L1 point (Sun-Earth Lagrange point) is the position in space where the Sun's gravity equals the Earth's, resulting in a "tug-of-war tie" for any object positioned there.

There is also the space-developing argument for the human race: The future colonization of space. Taylor et al. (2008)argues that, since commercial mining towns on Earth often become cities, the same may apply to space. The key elements to the future of humanity in space is, according to Taylor, water, propellant and other resources from asteroid mining for export. Furthermore, an affordable commercial logistics system needs to exist to support and stimulate sustainable growth for over 50 years, including perhaps remote resource recovery from Earth, to make the project successful.

However, there are of course some negative aspects to space exploration as well. As Thompson (2016) points out in the popular magazine *Wired*, there is also the risk for setting off a "star war". This could become reality if states continue their politics as before on Earth. However, it could be questioned whether it would be better or worse than wars on Earth have been, especially since there assumedly are relatively fewer civilians and fragile environments to consider as possible casualties.

Additionally, there have been made several studies on effects from rocket fuel on environmental and human health (Carlsen et al. 2007; Carlsen et al. 2008, 2009). It was found that rocket fuel as UDMH (Unsymmetrical DiMethylHydrazine) constitute a significant threat to both environmental and human health, especially where the burned-out rocket stages fall down. The human health issues related to UDMH could have carcinogenic, mutagenic, convulsant, teratogenic and embryotoxic characteristics. Compounds related to the *1,1-Dimethyl Hydrazine* fuel seem to be rapidly biodegradable, though lowering the microbial activity which could have unexpected environmental effects. Byproducts and transformation products seem to have low environmental toxicity, if they have not kept their original features.

Conclusively, the authors of *Harvest space for a greener Earth*(Matloff et al. 2014) suggest that:

"the growing awareness that we share the same world,
and that it has its limitations, began with those first photos of Earth taken from the Moon, the pictures of the fragile blue world drifting through an endless sky. They're probably right. If the human race ever does really coalesce into a family, I suspect those pictures will be hanging near the front door of the family estate."

LEGAL AND ETHICAL CONSIDERATIONS

Both companies display information on their websites regarding juridical legislation in space. They especially emphasize the new U.S. Commercial Space Launch Competitiveness Act (H.R. 2262) and call it a key milestone for the commercialization of space resources. Planetary Resources writes as follows:

"*In 2015, President Obama signed a historic piece of legislation into law that recognizes the right of U.S. citizens to own asteroid resources they obtain and encourages the commercial exploration and utilization of resources from asteroids*."

(PlanetaryResources 2015; DeepSpaceIndustries 2016f)

However, as Galliott (2015) points out, for the first time ever the possibility of venturing into space is no longer only for a privileged andwell-trained elite, and this inspires to much public enthusiasm. Alas, this excitement could provoke some practical and moral challenges as well, why as many potential consequences as possible should preferably be anticipated and understood. The privatization and commercialization, the risks for environment and human health, and the legal and responsibility issues should be considered according to the author.

Space Law is a special juridical case due to its endless frontiers; who has claim on something not within any country's borders?

The closest thing springing to mind is perhaps the Maritime Law of international waters. Dempsey (2016) explains Space Law as a "growing number of international, multilateral, and bilateral agreements and conventions, U.N. resolutions, decrees by international organizations, national legislation and regulations, and court decisions."

What these conventions mainly imply, is that they make any State responsible and liable for any activity in space - either by the government itself or any private party connected to it. This means a private company such as PR or DSI is to some extent representing the State where they reside. Furthermore, the responsibility includes authorization and supervision of their national activities, as well as notification of this to the United Nations, the public, and the scientific community.

Much of this is based on the "Outer Space Treaty" of 1967 (NASA 2006), where Manfred Lachs, later president of the International Court of Justice 1973-76, exclaimed that "*the acceptance of this principle removes all doubts concerning imputability*" (Dempsey 2016).

Environmental Protection is a related issue as well. Several States are concerned with the contamination of space environment, and have required licensees to agree to prevent contamination and to follow international guidelines for the mitigation of space debris (Dempsey 2016). It is also important to Earth's environment since some activities in space possibly could inflict damage to Earth. This is part of the assignments of the United Nations Committee for the Peaceful Uses of Outer Space. At least 26 States are involved in space law regulations.

If these national and international laws and conventions are broken, there would be severe consequences for the involved. In South Korea, a person who launches without authorization may be sentenced to up to five years in prison and pay up to fifty million won (Dempsey 2016).

However, many States have different approaches to space regulations; some are very strict, requiring insurances etc., while others seem to be open to much variation - India, for instance, has to date no proper space legislation at all (Dempsey 2016).

Dempsey (2016)concludes that States would be well advised to establish regulatory institutions to oversee space activities. The stated reasons are:

- Enhanced safety
- Protection of humans and environment
- To cover the costs of any future catastrophic loss
- To provide stability, predictability, and certainty essential for private commercial investment

Also, States should attempt to harmonize their laws with other States, producing a more homogenous and intact global approach towards space endeavors in general. With a more uniform legislation, juridical differences between States would assumedly be resolved with more ease.

DISCUSSION

Regarding the credibility of information: there are when considering future enterprises, such as the one in focus here, naturally a large amount of speculations and estimations included. Still, these speculations must be subjected to critical planning and scrutiny, as well as fitting physical calculations on a very high level. All this is necessary to accomplish a successful major asteroid mining mission. Along with the scrutiny and evaluation of the theories and plans, some well-placed critique could be helpful in finding and addressing any flaws or uncertainties which could easily be overlooked. This is important especially since much of the information is originating from companies which are looking to profit on these ventures, and are by definition prone to be biased in the fashion they deal out information publicly; it is certainly in their own self-interest to display the most positive version of their future enterprise as possible. Hence, it is relevant to be aware of this while reading and also to double-check main and critical points with other, independent sources.

This thesis set out to put a critical perspective on the future space enterprise and its implications, including the mentioning of any negative side effects that may arise. However, even if effort was put into finding and evaluating these problematic side effects, not many were found and it looks as if there are almost exclusively positive effects on humanity as a whole. To the reader, this could result in a seemingly biased report of the information provided about asteroid mining and space enterprise – could it really be that good in so many ways? One way to explain this could be that since the companies are researching this and hoping for investments, they stress mostly the positive aspects and that this is somehow affecting the scientific articles about the subject since the companies probably are funding a lot of the related research. Another way to explain it could be that science this far is limited to speculative and well-educated guesses, where the majority of negative aspects are not yet thought of or found out. This could conclusively result in a biased approach towards asteroid mining and is important to take into consideration.

In this study, almost all crucial information has been found on more than one platform to assure a more rational approach to the related information. Nevertheless, the aforementioned companies are in the space business, which is strongly connected to the rigorous and stringent science of astrophysics and space organizations such as NASA and ESA. This implies, along with the fact that the companies are official and to some extent representative for their nation, that there is some pressure upon them to produce accurate and trustworthy information. They will seemingly be liable for any misguidance made on purpose, which is not a good thing for serious, long-term companies which need investors who can trust them. Hopefully, this is enough reason to produce scientifically accurate data and provide it to the public in an unscrambled and unbiased manner.

The aforementioned methodology related to prospecting and space mining are still being developed, as it is an ever-growing field of research. Space exploration is still ”young” and there is much that needs testing before we can reach full assurance about anything related.

The chapter about remote sensing reveals many different ways to perceive an unknown object at a distance, of which some have been used for several decades and reached a status of certainty where the most flaws have been found out. On the other hand, some of the newer and more advanced methods are still in earlier stages of testing and require much data for analysis to develop. They could, however, give more detailed and precise estimations than older when functioning properly. Many authors writing about these methods are suggesting to combine them for a higher level of certainty about the observed asteroids supposedly containing valuable resources, and this seems like a good approach. PR and DSI are doing exactly this and showing which techniques work well together, such as with the Ceres sensors' HS and IR imaging.

However, full certainty of asteroidal compositions is probably hard to reach even with an advanced combination of RS monitoring. There are solar high-energy particles, galactic cosmic rays and micrometeorites continuously bombarding the celestial bodies, making their surfaces possibly altered and hard to categorize properly. When there have been more in-field observations and experiments on actual asteroids, more critical knowledge might be revealed, and when companies or governments are collecting the first asteroid material we will probably have a more exact knowledge on how to prospect more accurately in the future.

The RS and DSI approaches to space shuttle and harvesting technology are quite different but in some ways similar as well. They both use several smaller satellites for prospecting and larger ones for sampling or harvesting. This seems like a good approach considering the possibility of robotics being damaged in space and the argument for many fail-safes.

The financial feasibility of an asteroid mining mission seems very positive when regarding the estimated profit from a well thought-out mission. To be successful it is deemed essential to use a cost-effective plan with as many fail-safes as possible; in the emptiness of space there are no certain second chances if something goes critically wrong. And since much of the related science is based on remote sensing, speculations and estimations, any unknown factors could cause alarming issues. To prepare for these could prove the hardest challenge.
If one regards the sources in this thesis, many investors are prone to fund space commercialization which could be seen as an indication towards it being a feasible project - especially when successful and well educated people are investing officially the space business. Nonetheless, business speculations and investment is no scientific proof of anything but economist's and entrepreneur's own speculations and investment always includes risk-taking.

When harvesting asteroidal resources, industrially usable minerals are preferred since expensive minerals for only jewelry are not reasonable to harvest yet - prices will sink significantly on Earth since they are scarcity dependent. For instance, bringing home an asteroid consisting of only diamond would result in diamonds losing almost all value globally. However, in the short-term they could probably provide a profit, especially if supply is being controlled to keep the prices high. And since PGMs could be used for both jewelry and industrial purposes, they could just be transported to Earth and be sold to the highest bidder regardless of how they will be used.

Most side effects are seemingly beneficial to humanity, and this is logical since activity outside Earth's limits is probably funded, controlled and supported by humans with intentions for rather than against the human race, and a long distance to nature or life guarantees some level of lower risk than mining activities on the ground.
The research and growing understanding of asteroids and space is also used as advertisement by the reviewed space companies, both to colonize space and to avoid a direct impact by an asteroid. This seems believable since they are researching NEA's whereabouts in the solar system with intentions to anticipate and intercept dense M-type asteroids (the most significant threats) due to their estimated profitability, and anticipating orbits are a key element to

anticipating a future impact. Also, colonizing and developing the near-Earth space, which is a part of the plan, could probably help developing the possibility to deflect any such threat.

Some side effects could prove harmful to humanity. For example, seeing as the space law is not yet internationally conventional or harmonized it could result in conflicts, especially now since private parties are allowed to keep what they harvest in space (see page 30) there could be disagreements regarding some very valuable asteroids or other space resources. This could, in the turn, result in larger conflicts or "star wars" between companies or their respective nations which they are based in.

Further, the idea by NASA to bring home a whole asteroid (ARM), mentioned briefly in the "Metal Mining" chapter, seems like a possible dangerous idea if any technical malfunction occurs while bringing the asteroid towards Earth. If any error could result in a direct impact with Earth, the whole mission should probably be reinvented and planned anew. Any project risking human lives is worth reconsideration. A positive aspect is that the two reviewed companies do not mention any plan to bring home larger NEA's, only loose regolith or processed products. This is a good approach to minimize collateral damage and make themselves the only affected party if any part of the mission fails. Further, the main idea to keep as much as possible of the enterprise off-planet is also both cost-effective and reassuring for the public that they will not be directly affected by any possible mishaps.

Some negative effects on health and environment are presented about rocket fuel. Nevertheless, these effects are considered only with launches from Earth. The asteroid mining agendas described in this thesis are mainly focused on as few launches as possible, due to their high costs. Instead, they focus on relocating as much as possible to LEO or deeper space, so that harvesting, manufacturing and transportation can take place with as few lift-offs as possible. Consequently, the health-related and environmental impacts from rocket launches would assumedly decrease if fewer launches are necessary. Furthermore, the development of technology to use solar powered and hydrogen-based (LOx/H_2) transportations further decreases the toxicity of space enterprises in general since they are said to be clean energies.

The resources brought back to Earth, for instance PGM's, could possibly also prove some environmental issue when existing in abundance as never before. This could be an interesting topic for future studies: to reveal how sustainable it actually is to bring home alien metals and other resources and incorporate them in the global ecosystem.

When regarding space law, it is essential for any private party who ventures into space that, if they were to invest, they are also assured the rights to the profits from their endeavors. Otherwise there would be no incitement to venture into space for a private company.

Similar to as how multinational corporations work on Earth, the space industry could probably not be regulated by any single nation. Competition lowers prices and investors and clients will choose the one most profitable. The laws regulating the space market are a combined effort by several nations as well. There is of course the possibility that juridical regulations give the most powerful countries more rights to exploit space resources, since they may be writing the laws. Nonetheless, space will always be open to anyone who can get there, and if the methodology to do it violates any international treaties it is up to the other space-venturing nations to put pressure to follow the conventions. If as many space-interested nations as possible could agree on standard procedures and laws, a more defragmented and harmonious framework for future space ventures could be created.

Further, during the early days of commercial space activity, liability could be capped so as to encourage the investment and risk-taking necessary to establish an economic foothold in space.

Planetary Resources and Deep Space Industries are both very ambitious companies. There seems to be a huge difference though, when it comes to marketing. When googling Asteroid Mining, the first hit after Wikipedia is PR's homepage. This is surely no coincidence, since PR is backed by Google executives and other powerful investors who can control the media. They also have a more thought-out approach on their website with more creative story-telling on how they do their work. The layout is sometimes even a bit playful or "childish". However, this is probably very helpful in getting followers, investors and support in general. This style combined with events such as crowd-funding, publicly accessible space telescopes and appearing in media give the company a feeling of being very modern and open-minded. They also make constant updates on asteroid news and beta-testing of technology.

DSI, on the other hand, seems like a smaller company with fewer investors but a determined team. They have a more "geeky" approach using descriptions such as C3PO and Prospector-X. They do not appear as much in researched multimedia, and instead of having the creative and playful approach of PR, their videos use more of a style represented by Hollywood trailers where a dark and authoritative voice narrates the enterprise they are advertising for. This style make the whole idea to mine space for wealth seem like an amazing sci-fi/action adventure.

Both approaches are attractive in different ways, but in the end it is probably the marketing and the credibility of the companies that decide which one is given the most investments and thus the highest probability of success.

CONCLUSIONS

Space enterprise is possibly the next big 'gold rush' in the history of human kind and asteroids will presumably be its mines and fuel depots. Financial feasibility reports claim that an asteroid mining mission could be economically feasible and that NPV is the right measurement to be used as profitability estimation. One source says asteroid mining could be done by 2025 at a cost of 2.6 billion US dollars. However, to succeed with a space based enterprise a capitalization of 100 billion US dollars is recommended according to several sources.

The space market will be based firstly on water harvesting, which can be used for rocket fuel and other functions, and high value metals such as PGM's, which can be used to develop high-tech industries both in space and on Earth. Even with many risks included, the public support and financial backing is large. Also, since the privatization of space exploration has been growing, both thanks to technological and juridical development, the many versions on how to advertise, explore and prospect space have multiplied as well. The many methods and hardware needed to prospect space are constantly being evaluated, upgraded and updated and can now give a much more accurate model of space objects than earlier. The side-effects from this trend include: improved environmental monitoring, increased knowledge about asteroids and possibly the means on how to deflect one on collision course, more key resources for growing industries on Earth and possibly less mineral-related conflicts due to more sources of resources. In the long-term possibly also fewer lift-offs from Earth will be made, since they are very costly and represent the one largest environmental hazard. The reviewed companies are, according to their websites, focused on developing a space-based harvest and transportation system to cut down costs, which implies a development of near-Earth space and consequently perhaps colonization as well. The necessary buildings will be built by industrial metals such as Iron and Nickel found in abundance on certain asteroids. The two major companies use different commercial approaches and their own unique set of technology. In general, smaller space crafts are used to prospect and a larger is then harvesting the material in a various number of ways depending on resource and situation. Targeted asteroids are chosen depending on some specific physical variables and taxonomic type which describes the composition of the asteroid. The classification and verification of promising targets is done through combining different remote sensing techniques.

There are, however, still many unsolved issues related to asteroid mining as well. The space law is not fully standardized and conventional since nations have different approaches towards space travel and its commercialization. This could result in future off-planet conflicts and might as well have effects on Earth. Further, even though financial feasibility reports say it is possible to mine an asteroid for profit, perhaps even within 10 years, much information is still speculative and unknown variables could provide critical errors. Furthermore, the low amount of negative side effects found in this thesis could be a result of either lack of knowledge about them for now, since asteroid mining is still a future project which is now only in the test phase, or a biased projection of the data since the reviewed companies are funding and committing a large portion of the related research. There is also the possibility that there actually are many more positive aspects of asteroid mining than negative. Only time will tell for certain.

The ideas and projects presented in this thesis could well be the start of a paradigm shift for humanity. There are indications that the commercialization of space also could initialize the colonization of the same and provide the stepping-stone into deeper space as well as preventing an untimely death in the same fashion as the dinosaurs. The fact that these industries are among the fastest growing on Earth today, indicate that this could happen faster and earlier than believed before. The only incentive needed is a reason to risk capital to first venture into space for profit, which is already being done by the reviewed companies and their investors.

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