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Viktor Maximilian Bauer BSc

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Contents

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abstract

Asteroids are a potential source of valuable materials and precious minerals. While some would be easy to access, most of what we know today about asteroids is based on reflectance spectra and only a few missions to selected objects. This master thesis focusses on reviewing our knowledge about asteroids,their spectra, compositions, orbits and environments, as well as potentially valuable materials that could be gained by mining asteroids. Further, several potential ways to mine asteroids, proposed by scientists all around the world are explained and analyzed. The last chapters focuss on the non-scientific problems ahead of asteroid miners, and discusses how profits could be made on the world market with asteroidal materials. It concludes with a summary of the various space laws and their implications for asteroid miners, and a discussion about the main scientific problems of asteroid miners, ideas how these could be dealt with, and the next logical steps towards the realization of establishing a clean source of vital materials.

abstractDE

Asteroiden sind eine potenzielle Quelle fuer Wertvolle Materialien und Mineralien. Obwohl einige von ihnen sehr einfach zu erreichen sind, stammt das Meiste was wir heute ueber Asteroiden wissen nur von observierten Spektren und einigen wenigen Missionen zu Near Earth Objects. Diese Masterarbeit fokussiert auf eine Zusammenfassung von unserem derzeitigen Wissensstand ueber Asteroiden, ihre Spektren, Zusammensetzung, Orbits und Umgebungen, sowie auf die Materialien welche wir durch Asteroidenbergbau schuerfen koennen. Des weiteren werden verschiedene von Wissenschaftlern vorgeschlagenen Konzepte des Asteroidenbergbaus erklaert und analysiert. Die letzten Kapitel dieser Arbeit examinieren die wissenschaftlichen und nicht-wissenschaftlichen Probleme des Asteroidenbergbaus, und erarbeiten auf welche Mechanismen Ruecksicht genommen werden sollte um tatsaechlich auch Profit mit den aus Asteroidenbergbau gewonnenen Materialien gemacht werden koennte. Der Schluss dieser Arbeit konzentriert sich auf die rechtliche Lage im Asteroidenbergbau, und legt verschiedene Strategien dar um mit wissenschaftlichen und technischen Problemen umzugehen um eine neue saubere Quelle fuer die Gewinnung von Ressourcen zu erschliessen.

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Ich habe mich bemüht, sämtliche Inhaber der Bildrechte ausfindig zu machen und diese ordnungsgemäß in den Bildunterschriften anzuführen. Sollte dennoch eine Urheberrechtsverletzung bekannt werden, ersuche ich um Meldung bei mir.

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Chapter 1

Introduction

Since the beginning of our history, mankind had always only one source of raw materials: they had to be carved out of our own planet's body. The environmental impact by exploitation of these natural resources range between minor and catastrophic, and many examples in our history bare witness of tremendous effects. Whether this would be the extreme de-forestation for coke production during the early stages of metal working, found in pre-historic accounts, the heavy metal pollution in the South-American wilderness by gold and silver mines, or the most concerning climate change due to the rapid release of CO_2,that was stored as fossil fuels for millions of years. However, all good things come to an end eventually, and Earth Overshoot Day (previously the Ecological Debt Day), the day when Earths resources for that year are depleted, steadily marches to come earlier each year. Earth's crust will eventually be depleted of all resources we so desperately need to fuel our economy.

However, mankind also has shown that it can become inventive once problems reach a critical point, and in this case the answer may be to look for the stars, or more precisely to the vicinity or our own star: the celestial bodies of our solar system. Science fiction has brought up the possibility of gathering the resources we need, from asteroids decades ago, and as in many cases, science fiction may here too become science fact eventually. Asteroids are the smallest celestial bodies, floating around the sun by the millions and loaded with precious materials, potentially feeding our ever-growing economy for thousands of years, if not longer. The idea is not new exactly, as mankind has unknowingly practiced the exploitation of asteroid resources thousands of years ago. The iron age could never have happened without it, as terrestrial iron has not occurred in a metallic state since the first bacteria oxygenized Earth, binding iron as iron-oxides in the process, which could not be processed until the invention of iron smelting. The oldest findings of iron artifacts, dating back to 3200 BC have been discovered to be made out of meteoritic material. Now, it seems the time has come when asteroids help us again, achieving tremendous scientific and economical progress, by establishing a constant flow of precious raw material to Earth.

The topic of asteroid mining has recently achieved more and more attention in the eyes of politicians, entrepreneurs, and the public. With the possible profits going into the billions, financial instincts have become a dominant factor in the development of such endeavors. Greed has often proven to be a most influencial motivator to advance mankind's progress in many ways. Many companies have formed, planning on exploiting asteroids to their own, and mankind's profit. Still, there are many obstacles lying ahead before the realization of asteroid mining. These problems are of scientific, financial, economic, legal, and technical nature, and they will take years to cope with. Yet the first steps are done, and eventually we will do the next vital step in expanding our new frontiers further out into space.

Chapter 2

Asteroids

2.1 Formation

An understanding of the formation of asteroids is key to understand why asteroid mining could pose a lucrative economic alternative to terrestrial mining, and it begins with the formation of our solar system.

The Galaxy contains molecular clouds which in contrary to the common interstellar medium do not consist of hot, ionized gas filling the vast gaps between stars, but rather cold and dense molecular hydrogen in combination with a small percentage of other materials. Due to the sheer density of the clouds they can, under the right circumstances gravitationally accrete to form stars and later planets under the influence of magnetic fields. (Trigo-Rodríguez et al., 2017) There is ample scientific evidence that within these molecular clouds many different pre-solar nebulae gravitationally collapse to form proto stars, many of which develop their own solar systems, enhanced by the activity of red giants and supernovae. (Lada and Lada, 2003; Adams, 2010; Bouvier and Wadhwa, 2010; Messenger et al., 2003; TRIGO-RODRÍGUEZ et al., 2009; Trigo-Rodríguez et al., 2017)

When the proto-sun started to form by collapse, the temperatures in the surrounding area was by far too high to allow for minerals to condense from the gas phase to solid state, but once the major part of the gas around the newly forming sun was dragged into it, sparking its nuclear fusion processes. The solar wind, a result of the suns nuclear activity swept most of the gas from the circumstellar medium. Combined with the gas drag to the gas giants that most likely appeared only a few million years after the sun's formation, the radiation pressure decreased the gas density so that the overall temperature was with approximately 2000K low enough for solid materials to condense into small mineral particles. (Williams and Cieza, 2011; Lewis, 1974; Cameron and Fegley, 1982; Trigo-Rodríguez et al., 2017) These particles of solid material did then no longer fall under the rules of gas pressure, controlling the shape of the sun-surrounding envelope and started to settle, most likely due to the rotation of the medium. By slowly falling towards the ecliptic

plane, they formed the protoplanetary disk. (Trigo-Rodríguez et al., 2017; Taylor et al., 2001) Of course this is as all other models just an approximation, and most of the different steps would most likely have happened at least partially parallel.
Since the rather high temperature distribution factor of the gas became less and less important with its decline in pressure, the thermal conditions in the different parts of the protoplanetary disk ranged from rather cool in the outer segments of the newly forming solar system to rather hot in the inner areas. Thereby the inner disk was largely dominated by materials with a high condensation temperature like various refractory oxides and especially metals like iron, nickel, but also silicates. The outer region, lying behind the so-called snow line, the distance to the sun where water could enter the solid-state phase, showed a high abundancy of dust, hydrated minerals and ices, which mediated for complex organic materials to form chemically. The materials forming in the cool environment of the outer regions where caught in the gas drag and suffered a constant decay moving inwards the protoplanetary disk where they were partly vaporized again. (Cuzzi et al., 2008; Willacy et al., 2015; Trigo-Rodríguez et al., 2017) Simultaneously the young sun with its extreme magnetic activity in combination with disk interaction produced X-winds, high speed jets, which drove the high temperature condensates from the inner region outwards. (Shu et al., 1996, 1997; Trigo-Rodríguez et al., 2017)
With only parts of the condensates re-evaporating and a constant rate of condensation and migration, the concentration of particles became higher and higher, eventually leading to coagulation of minerals, allowing them to stick together and form ever larger lumps. At a certain size, gravitational forces became high enough for the runaway growth to begin, leading these small bodies of condensates to fuse over time to even bigger ones, eventually leading bodies to achieve kilometer-size. (Blum and Wurm, 2008; Trigo-Rodríguez et al., 2017)
These so called planetesimals are together with their smaller counterparts basically the building blocks of almost every celestial body in our solar system, that did not already exist back then. Some of them managed to accrete enough other ones, especially within the oligarchic growth period which sets in when the largest proto-planets dominate the dynamics of the disk, to become the planets present in our solar system today. Others stay small and never get the chance to grow at all, and some grow to a large size, only to be crushed by a collision with another. (Goldreich and Ward, 1973; Cuzzi et al., 2008; Trigo-Rodríguez et al., 2017)

Thus, asteroids, the remnants of planetary formation, have largely the same overall composition as the terrestrial planets that formed during that periods. However due to the extreme differences in the various formation and evolution of asteroids, that only accounts for the combined mass of asteroids, not for the single asteroids, which tend to have extremely different compositions compared to each other as explained in the Asteroids section.

When planetesimals formed, they evolved mostly depending on their respective accretion time and place, size, and direct composition. When they reached a certain size enough for the thermal heating of their interiors to excel the amount of heat radiated from their surface they started to melt. The main isotopes contributing as thermal sources by radioactive decay were ^{26}Al and ^{60}Fe with halftimes of 0.74 and 1.5 million years. (Cameron and Truran, 1977; Meyer and Clayton, 2000; Takigawa et al., 2008; Wasserburg et al., 2006; Trigo-Rodríguez et al., 2017) The short halftime means that the major heat source for planetesimals worked solely for the first 1.5-2 million years. As seen today the very large objects like Earth with enough mass to surface ratio could of course still maintain a considerable temperature due to other radioactive elements decaying in its interior, but smaller planetesimals forming in a later period remained cool. The asteroids coming from these early planetesimals have undergone differentiation, a process that occurs when a body stays in liquid state long enough for the heavier elements to settle towards the interior with the lighter materials being pressured to the surface of the object. (Trigo-Rodríguez et al., 2017) Depending on the timescale and the size of the primordial body there are different stages of differentiations, for example when objects became hot enough for them to melt but not nearly long enough for their interior to differentiate entirely. Other asteroids that formed later did melt eventually but only partly, and therefore formed a solid block that had still a rather homogeneously distribution of components. Others still have not even had enough thermal energy for them to melt at all, because they either didn't reach the size necessary, or lost most heat to diffusion through their extremely porous outer layers. (Trigo-Rodríguez et al., 2017; Wetherill, 1989; Froeschle and Greenberg, 1989)

2.2 Classification

As seen in the previous sections asteroids can be roughly divided into differentiated asteroids, those who have undergone severe melting to the point where the heavier elements have settled to the center of the bodies, and undifferentiated asteroids, a group that has been only partially molten or not even at all, that shows no significant change of composition over the entire body. However, these differentiated and undifferentiated show to much a variety as this simple classification would serve scientists. Thus, there are two more ways to classify asteroids, based on their spectral behavior and their orbital characteristics.

2.2.1 Spectral Classification

The assumption there is, that the emission spectrum corresponds to the surface composition, and that the overall composition should not differ too much within

the entire body. Thus, the surface properties like grain size, mineralogy, and degree of space weathering of an asteroid can be inferred through spectral and photometric measurements at the wavelength from ultra violet to infrared. For detailed studies of asteroids, especially in respect to asteroid mining, a full mineralogical analysis would of course be best suited. But for such an analysis, only the best quality spectra are good enough and these are only available for very few asteroids. On the other hand, simple taxonomic classifications can be done using lower quality and lower resolution spectra, enabling us to characterize asteroids rapidly. Hence, while the availability of high resolution spectra is limited, the taxonomic classification is available for orders of magnitude more. Despite not having the best resolution for every single asteroid, those with similar taxonomic class should have a similar surface composition.
There exist many different taxonomic systems like the Tholen, the SMASS, and the Bus-DeMeo classification. Since most of them are rather similar I will focus on the latest, the Bus-DeMeo taxonomy, which was created to extend the earlier SMASS (or Bus and Blinzel) taxonomy from the visible spectra to the near-infrared as consistent as possible, since the visible to 1 micron wavelength, used by the earlier SMASS and Tholen taxonomies was no longer sufficient the more asteroids were found, and the farther the observational methods developed. (Tholen and Barucci, 1989; Bus and Binzel, 2002; DeMeo et al., 2009; Trigo-Rodríguez et al., 2017) In accordance to the Bus-DeMeo Taxonomy (see Fig. 2.1), asteroid spectra are traditionally divided into three major complexes (or types), each of them being divided in several sub-classes.

2.2.1.1 C-Complex

C-Complex derived its name in connection to the carbonaceous chondrite meteorites. With about 75% of all asteroids being C-type, they are the largest taxonomic class. They generally have a low albedo surface with about 0.05, and their spectra show flat to low slopes and are subtly featured to featureless. 'Subtle features' means that they have absorptions of merely a few percent, the most notable being the 0.7 micron feature, that indicates the presence of phyllosilicates, most likely due to aqueous alteration. (Vilas and Gaffey, 1989; DeMeo et al., 2009)

2.2.1.2 S-Complex

S-complex was originally named for its suspected silicaceous composition. With about 17% they are the second largest type of asteroids. They have an albedo between 0.15 and 0.25, and their spectra are characterized by moderate silicate absorption feature at 1 and 2 microns. (DeMeo et al., 2009; Chapman et al., 1975)

2.2.1.3 X-Complex

X-complex is a rather variable type, since they comprise the lowest and highest albedo ranging from merely a few percent up to 50, and due to that is has long been argued that they are compositionally degenerate. They are characterized by moderately sloped and subtly featured to featureless spectra. (DeMeo et al., 2009)

Additionally, there are several spectral classes, that do not fit in with any of the three major complexes. They are however by far less numerous than the first three groups, and most of them have by far more extreme and distinct features than the others. These other classes include the spectrally olivine-dominated A-type posing a broad and deep 1-micron feature, the spectrally featureless and very red-sloped D-type, and the spectrally olivine-dominated V-type showing a narrow and deep 1-micron feature and a broad, deep 2-micron feature. (DeMeo et al., 2009) However the taxonomic types give more of an overall classification system, and should not be viewed as exact representations of composition, respective evolution, or even real similarity. It is hard to 'correctly' classify asteroids, since an object classified by visual wavelength alone may change its type when the wavelength coverage is extended to the near-infrared.

2.2.2 Orbital Properties

Another way to classify asteroids is due to their orbital behavior, the way they take around the sun. To do that we use their orbital elements, these are a set of parameters that describe orbital motions and absolutely suffice to predict a bodie's exact position at any given time. When using Keplerian elliptical orbits there are six orbital elements. The semi-major axis a, the eccentricity e, the inclination i, the longitude of the ascending node Ω, the argument of pericenter (also called perihelion when the sun is the center body) ω, and the mean anomaly M. Hereby a and I define the size and the shape of the ellipse, i and Ω define the orientation of the orbital plane of the ellipse, ω defines the orientation of the elliptical orbit on its plane, and M defines the position of the body on the elliptical orbit at a specific time.(Novaković, 2013)
There are many ways to disturb the orbital behavior of such lightweight celestial bodies as asteroids. One of the more common ones are resonances. An orbital resonance is a gravitational phenomenon that implies similarity between the frequencies of bodies that are orbiting around the same gravitational center. Throughout the solar system orbital resonances are ubiquitous in their existence, like the Trojan asteroids that are in 1:1 resonance around planets or the Iovian moons Io, Europa, and Ganymede in 1:2:4 resonance. (Malhotra, 1998; Novaković, 2013) Since resonances can be both, a source of long term stability, and instability, these mechanics are vital to understand the distribution, the transportation and the dynamical lifetimes

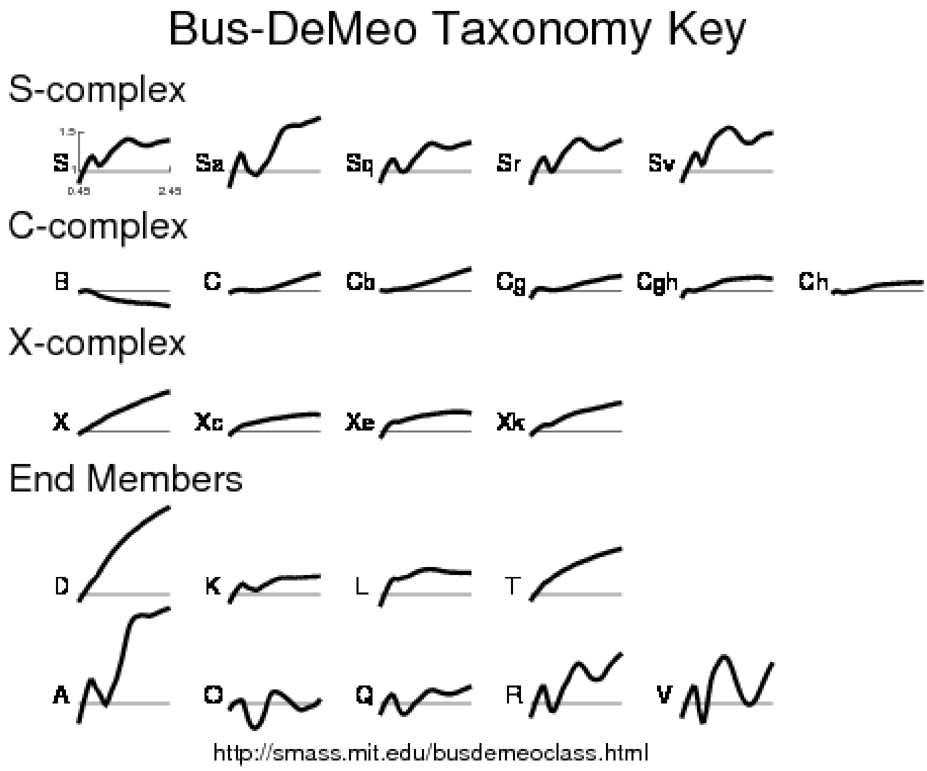

Figure 2.1: Bus de Meo spectral classification scheme, (DeMeo et al., 2009)

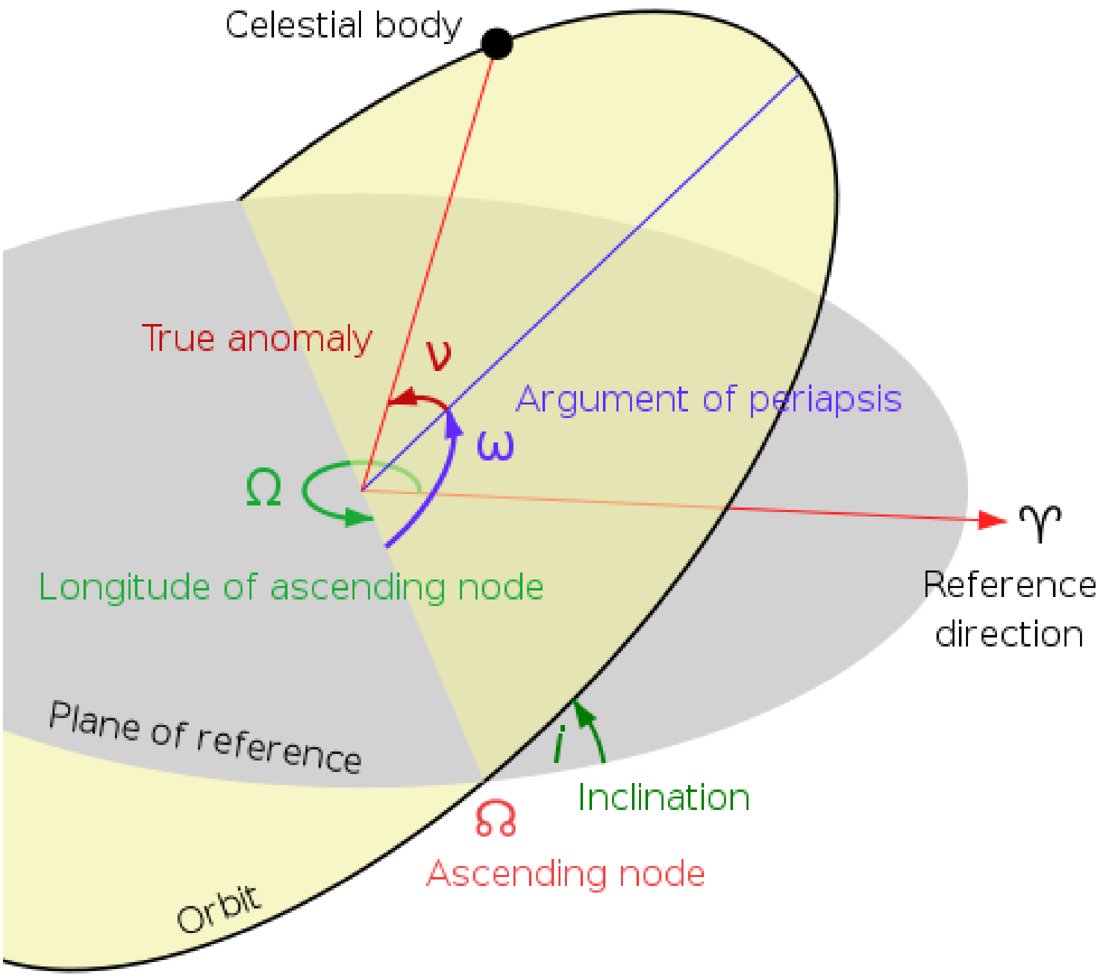

Figure 2.2: The orbital elements and their relationships, (Novaković, 2013)

of asteroids. For asteroids, there exist two very important types of resonances: the Mean Motion Resonance, and the Secular Resonance.

Figure 2.2 Shows the orbital elements.

2.2.2.1 Mean Motion Resonances

Mean Motion Resonances occur when the orbital periods of celestial bodies (in this case an asteroid and a more massive body like a planet or dwarf planet) follow a ratio of small integers. In example when a planet takes rather exactly twice the time for one entire orbit than the asteroid. When k and k_p are positive integers and n and n_p are full orbital periods of an asteroid and a Planet p, then a mean motion resonance can occur when $kn - k_p * n_p \approx 0$. This is of course also the case when more Planets are in resonance with the asteroid. (Nesvornỳ and Morbidelli, 1998; Novaković, 2013)

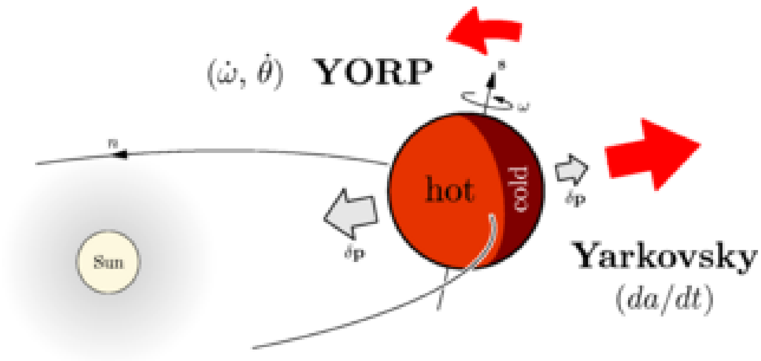

Figure 2.3: Schematic description of the YORP and Yarkowsky effects, (Novaković, 2013)

2.2.2.2 Secular Resonances

Secular Resonances occur by commensurabilities between the orbital precession rates of an asteroid with planets. These resonances influence rather slow angles like for example the argument of the pericenter or the longitude of nodes. (Knežević et al., 1991; Novaković, 2013) These secular resonances are strongest when a secular frequency of an asteroids secular angle is equal to the matching frequency of a major planet. One very prominent example is the so called ν_6 resonance, which is thought to be of great importance in the delivery of fresh asteroids to the proximity of Earth. The 6 in this case stands for the sixth planet in the solar system Saturn. (Knežević et al., 1991; Novaković, 2013)
Apart from resonances however, the dynamic stability of asteroids is also strongly influenced by thermal phenomena. The two most important ones are the Yarkowsky and the Yorp effect.

2.2.2.3 The Yarkowsky Effect

The Yarkowsky Effect results from the partial absorption of the solar radiation and consequential anisotropic re-emission at infrared wavelengths, due to the fact, that always only the noon side of an asteroid is heated by the sun. This side becomes by far hotter than the night side, thus the re-radiation into the direction of the sun is dominant over that into radial direction, taking by far more linear momentum away. This imbalance in the respective directions results in a recoil force away from the sun. The Yarkowsky effect mainly influences the semi-major axis of an asteroid. The recoil forces are of course by far weaker than gravitational effects of planets or the sun on the asteroid orbit, but given timescales of hundreds of million years, it can still lead to significant orbital changes. (Bottke Jr et al., 2006; Novaković, 2013)

Figure 2.3 Shows a schematic description of the YORP and Yarkowsky effects.

2.2.2.4 The YORP Effect

The YORP Effect occurs when an asteroid of irregular shapes reflects and re-emissions the energy of solar radiation. The irregular shape causes an irregular distribution of the energy and results in a net thermal torque on the body. This torque, over time affects the spin rate and the obliquity of the asteroid suffering it. The Yorp effect is so important because it controls the magnitude and the direction of the Yarkovsky recoil drift and the long-term evolution of the asteroid's spin vectors. (Bottke Jr et al., 2006; Novaković, 2013)

As one can imagine, the importance of the Yorp and Yarkowsky effect lies within its permanent working and less within its rather small magnitude of force. Both effects depend largely on the amount of solar radiation reaching the surface, thermal inertia, rotational period, and spin obliquity, but most importantly on the size. Since the surface grows not nearly as fast as mass by larger radii, the two effects become less and less important once a certain size is reached and the inertia of the mass becomes dominant. Therefor they influence smaller asteroids' orbits by far more than those of larger ones, up to a maximum size of about 30 kilometers. (Bottke Jr et al., 2006; Novaković, 2013; Rubincam, 2000)

2.2.3 The Main Belt

The asteroid belt is the last remnant of the original planetesimal population within the inner solar system. All asteroids that orbit around the sun between the orbits of Mars and Jupiter, meaning a semi-major axis between 2.1 and 3.3 AU are called main belt asteroids. The main belt is the largest reservoir of asteroids within the inner solar system and is made up of hundreds of millions of asteroids. With a combined mass of about $3 * 10^{18}$ metric tons of material, the main belt has only about 4% of the mass of the moon, or 22% that of Pluto. (Petit et al., 2002; Novaković, 2013) However almost one third of the main belt's mass is contained within its four largest objects Ceres, Vesta, Pallas and Hygiea. Most likely the main belt has lost most of its initial mass to orbital instability and collisions with planets. Current estimations are that up to 99.9% of the primordial mass has been depleted. (Petit et al., 2002; Novaković, 2013)
One typical characteristic of main belt asteroids is that the dominant composition of main belt asteroids seems to change with heliocentric distance. (Gradie et al., 1989; Novaković, 2013) The mass of the inner main belt (2.1-2.5AU) is dominated by S-complex asteroids. The central belt (2.5-3.2AU) is dominated by C-complex asteroids, and the outer main belt with the Jupiter Trojans (3.2-3.7AU) is dominated by the P- and D-type taxonomic classes. (Gradie and Tedesco, 1982) That suggests that either the asteroids there stayed at their original positions or suffered

similar orbital modification, leading for them to stay close together. However, 'dominatedâĂİ means that there are different taxonomic types mixed within each dominant regime, most likely due to respective orbits having been influenced by various effects like the Yarkowsky and Yorp effect or by gravitational forces of either the major players in the main belt Ceres, Vesta, Pallas, and Hygiea or by Jupiter.
The second typical characteristic of main belt asteroid population is their extreme orbital excitation, meaning the orbital elements i and e are quite large. This is due to Jupiter who, with its extreme gravitational effects on its surroundings induces mutual perturbations among the main belt asteroids, causing collisions and dynamical excitation. Sometimes making the asteroid orbits unstable. (Petit et al., 2002; Weidenschilling, 2000; Novaković, 2013)
Unfortunately, these main belt asteroids are rather hard to come by, requiring extreme amounts of energy and long travel times to reach. Round trip journeys take up to a decade with current technologies, making investments in mining them unattractive for now.

2.2.4 NEOs/NEAs

Near Earth Asteroids are those with a perihelion distance smaller than 1.3AU and aphelion distance greater than 0.983AU, thus those who have orbits that approach or even cross Earth's orbit eventually. Often, they are also referred to as Near Earth Objects since an unknown number of them may be dormant comet nuclei. Every object that is discovered without the characteristic tail of a comet is classified as an asteroid, even though that may not be exactly true. Despite the NEOs being by far less numerous than the main belt asteroids, they are of utmost importance for asteroid mining, since many of them require lower mission velocity than even missions to the moon. This is mostly due to their relatively low discrepancy in velocity in respect to Earth's own δv, In addition to the fact that some of them come by definition very close to Earth (Xu et al., 2007; Novaković, 2013)
By 3rd of June 2017 16,294 NEOs have been identified, 106 of which have been classified as comets, mainly by ground based optical surveys. In sizes, they range from a few meters up to $\sim$ 40 kilometers in diameters (1036 Ganymed). NEOs of larger diameter than 1kilometer were estimated by Bottke et al. (2002) to be about 960 ± 120 which is in good agreement by more recent findings of NEOWISE . Mainzer et al. (2011) argued that with some 2700 objects with 100m-300m diameter NEOs known, about 80% remain undiscovered.(Bottke Jr et al., 2002; Novaković, 2013; Mainzer et al., 2011) Overall, they predicted the number of NEOs down to 100m in diameter to be $20,500 \pm 3000$, and those with a diameter larger than 50m some 80,000, which is about a factor of four smaller than earlier estimations. (Bottke Jr et al., 2002; Novaković, 2013) Those NEOs smaller than 50m in diameter

are extremely hard to detect directly. Smaller NEOs are most certainly high in numbers though, following a line of slope indicating that there will be no more than 100 times more NEOs a tenth the size in diameters than any given size. It is estimated that about 1 million near Earth asteroids with a diameter smaller than 40m should exist, with only 1% of them having been identified. Currently the small end of the size scale of NEOs is pinned at the rate at which fireballs are detected in Earth's atmosphere. (Brown et al., 2002; Novaković, 2013) The current NEO discovery rate is about 1000 per year.

The reason why there are so few NEAs compared to main belt asteroids is due to their overall dynamic stability. Numerical integrations have shown that the typical orbital lifetime of NEAs is about 10 million years. They are usually either destroyed by a collision with either the sun or a planet, or get eliminated by being ejected out of the solar system within an astronomically short time-period. (Novaković, 2013)

The dynamics of the NEA population is strongly influenced by various resonances, like the mean motion resonance. The MMRs are by far weaker for NEAs than for their main belt counterparts because the terrestrial planets are by far less massive than Jupiter, however MMRs that are located interior to Mars are very dense, and they often overlap with each other, expanding the chaotic zones, and making orbital behavior extremely hard to predict for the longer term. Additionally, every close encounter with a terrestrial planet gives rise to an impulse velocity to the bodies velocity, causing its semi-major axis to change instantly. (Bottke Jr et al., 2002; Novaković, 2013)

The short lifetime of NEAs means that they are not primordial objects but instead transported to an inner Mars orbit, most likely from the main belt. It is a reasonable hypothesis that the population of NEAs derives from the so-called Kirkwood Gaps in the main belt. In these areas, a number of rather weak resonances (in comparison with the 1:1 Jupiter MMR) like the $\nu_6$resonance, the 3:1 Jupiter MMR and the 5:2 Jupiter MMR work on large time scales, clearing the ever-replenishing Kirkwood Gaps ejecting a substantial amount of the asteroids either out of the solar system or kicking them into the sun, with only a small proportion finding their path on a Near Earth Orbit. (Nesvorný and Morbidelli, 1998; Novaković, 2013; Elvis, 2013)

Traditionally NEOs are divided into different asteroid families, groups of asteroids that have the same or similar orbits. These families are named after the first Asteroid of each which was discovered There are three major families: the Aten Asteroids, the Apollo Asteroids, and the Amor Asteroids.

2.2.4.1 Aten Asteroids

Aten Asteroids are those with an orbital semi-major axis smaller than 1AU and aphelion distance greater than 0.983AU. They are considered the smallest of the three NEO families and named after the asteroid 2062 Aten which was discovered in 1976. It is estimated that about $1,600 \pm 760$ objects larger than 100m in diameter and 42 ± 31 larger than 1kilometer belong to this family. Most of the time their orbits lead them around the sun interior to Earth's orbit, however occasionally they may cross or even collide with it. (Mainzer et al. 2012)(Mainzer et al., 2012; Elvis, 2013)

2.2.4.2 Apollo Asteroids

Apollo Asteroids have a semi-major axis greater than 1AU and a perihelion distance smaller than 1.017AU (the aphelion distance of Earth is 1.017AU). They are named after 1862 Apollo, which was discovered in 1932 by Karl Wilhelm Reinmuth, and are the largest group of NEAs with some 4,500 asteroids of this family being discovered, and are thought to make up to 62% of all NEAs. (Bottke Jr et al., 2002) Mainzer et al. (2012) estimate a total number of 462 ± 110 asteroids larger than 1 kilometer in diameter and $11,200 \pm 2,900$ asteroids larger than 100m. Two of the most prominent family members are (25143) Itokawa, the first asteroid to be targeted by a sample return mission by the Japanese space probe Hayabusa, (54509) YORP who delivered the first direct observational evidence for the YORP effect when its rotation rate was determined, and (3200) Phaeton is believed to be the parent body to the Geminids meteor shower. (Chesley et al., 2003; Taylor et al., 2007; Novaković, 2013; Elvis, 2013)

2.2.4.3 Amor Asteroids

Amor Asteroids are defined by a perihelion distance between 1.017AU and 1.3AU This means that while this family's asteroids can come rather close to Earth's orbit, occasionally even to Earth itself, they can at least currently not collide with it. The first Amor to be detected was also the first NEA to be identified (433) Eros. With its 17 kilometers in diameter it is one of the largest NEAs in existence, second only to another Amor asteroid (1036) Ganymed, with an estimated diameter of about 32 kilometers. Up to this point about 3,800 Amors have been identified, while estimations reach up to 320 ± 90 members above 1 kilometer in diameter and $7,700 \pm 3,200$ larger than 100m. Thus, they are the second largest NEA family. (Mainzer et al., 2012; Novaković, 2013; Elvis, 2013)

Every NEA belongs to one of these groups, but for the purpose asteroid mining as well as its scientific counterpart planetary protection, two more major distinctions should be considered.

2.2.4.4 Potentially Hazardous Objects

Potentially Hazardous Objects are asteroids that are currently defined on a set of parameters which measure the asteroid's potential to approach threateningly close to Earth, while being large enough to cause severe devastation on the population of an affected area. Every Asteroid that has a minimum orbit intersection distance of less than 0.05AU with the Earth (about 20 times further out than the Earth-Moon distance) or a size greater than 150m in diameter, is considered a PHO. (Elvis, 2013; Novaković, 2013) Of course these parameters are just an approximation to how dangerous asteroids are, and there are probably many asteroids that are not considered PHOs, that could be dangerous. The devastation an impact could cause depends on multiple factors like the density, the composition, the material strength, the relative impact velocity, the impact angle, and the exact impact location. An impact in the middle of the sea would for example not produce a giant dust cloud that could shadow Earth's surface around the globe for days, weeks or even months, however such an impact would cause giant tsunamis that could drown the coastal areas of an entire ocean.

However dire the situation could be once such an PHO smashes on the Earth, the very fact that they are larger than 150m and periodically approach rather close to Earth make them promising targets for asteroid miners, since many of them could be reached rather easily with equipment, while also by definition having a lot of material present that can be mined. It has been argued that to be profitable the first mining missions to asteroids would have to go towards targets with at least 100m in diameter, since otherwise the initial launch and development cost for the equipment would not be compensated by the material at hand. (Elvis, 2013; Novaković, 2013)

2.2.4.5 Earth co-orbital Asteroids

Earth co-orbital Asteroids have either the same or an extremely similar orbit to that of Earth and are in a 1/1 mean motion resonance with our planet. Despite all Earth co-orbital Asteroids belonging to one of the three NEA families, they have very distinct characteristics and are often treated separately. Depending on the various points of libration, there are several classes. The Trojans are the most common and well-known class, located in the L4 or L5 Lagrangian points, 60 ahead or behind the planet on its orbit. While Trojans around the massive gas planets are long known, the existence of Earths Trojans has been confirmed when the first of them 2010TK7 was discovered. Their orbits are extremely robust and they can remain stable despite closing in on the planet up to four Hill radii. (Connors et al., 2011; Elvis, 2013) The other important ECOA class are the horseshoe companions. Their name derives from the very horseshoe like orbit, on which objects liberate around 180° from the larger body. Other than Trojan satellites, horseshoe companions are not considered as long-term stable co-orbitals and have liberation periods and orbital lifetimes that range from several hundred to many thousands of years, however more recent findings suggest that under certain conditions like a primary to secondary mass ratio larger than 1200 they could be stable for quite some time. (Elvis, 2013; Novaković, 2013; Ćuk et al., 2012)

Overall, ECOs present many advantages over other NEAs for asteroid miners, as their prolonged proximity to Earth enables longer term communications. Additionally, the commensurability to Earth's orbit, means that a steady flux of solar radiation, the main source of power for most space probes and suggested asteroid mining techniques, while also keeping the thermal inequality between perihelion and aphelion as low as possible, thus only the noon/night temperature difference on the asteroid surface troubles the engineers when such an ECO is targeted. Theoretical studies show that low-inclination co-orbital orbits are less stable than high inclination orbits. Since inclination is the factor most relevant for delta-v requirement of rendezvous missions. This does not mean that their actual delta-v is low compared to Earth, but to reach the position of such an asteroid requires by far less energy than for some rendezvous missions already done. (Stacey and Connors, 2009; Novaković, 2013; Elvis, 2013) While this makes not the mining itself more practicable, it would help a lot by learning how to determine the composition of asteroids and link their taxonomic type to Meteorites.

Chapter 3

Meteorites

3.1 Classification

The goal of meteorite classification would be to group all meteorite specimens that share the same origin or come from the same parent body, like a planet, moon, asteroid or comet. However due to the lack of knowledge considering the composition of the various celestial bodies, especially for asteroids and comets, this seems at least for now out of sciences abilities. Instead, for the time being Meteorite classification relies on grouping the available meteorites into classes that share certain distinct characteristics physical, chemical, isotope, and mineralogical properties. Thus, different meteorite group could derive from the same heterogeneous parent body, while meteorites from the same groups could come from different asteroids, that share a similar composition and mineralogical evolution.(DeMeo et al., 2015)

The first separation of meteorites is into un-melted chondrites and melted non-chondrites. Generally, it is assumed that chondrites derive from undifferentiated parent bodies, while non-chondrites have their origin in a differentiated one, however it may be possible that some chondrites were formed in the cool and therefore un-melted crust of a differentiated asteroid. (Weiss and Elkins-Tanton, 2013; Krot et al., 2014) For further separation of meteorite types, the best tools to classify, despite poor understanding of the exact processes involved, are their primary (nebular) and secondary (parent body) physical and chemical characteristics. For a bulk chemistry based classification, it is usually sufficient to rely on some representative element ratios that represent the major fractionations that influence meteorite composition. The most outstanding bulk composition is that of CI chondrites since they have almost exactly (within scientific errors) identical element abundancies as the rock-forming component of the solar photosphere. Since all celestial bodies are thought to have formed one way or another from solar composition, the elemental ratios are usually normalized to the CI Chondrites. Especially oxygen isotopes have proved to be very useful to classify meteorites, because they show mass-independent variations (most physical and chemical processes involve mass dependent fractionations), however other isotope fractionations are more and more used as an additional classification tool. (Krot et al., 2014; Weiss and Elkins-Tanton, 2013; DeMeo et al., 2015)

As with the asteroid taxonomic group there is a significant number of meteorites that does not seem to fit within the established groups. These count as ungrouped, since conventionally a group must consist of at least five members. If we assume that one group originated in the same parent body, and that every ungrouped meteorite comes from a different parent body, the meteorite collection on Earth would appear to be sourced by 100-150 distinct parent bodies. (Burbine et al., 2002; DeMeo et al., 2015)

3.1.1 Chondrites

Chondrites mainly consist of three major components. Embedded within a fine-grained matrix, there are refractory inclusions and chondrules. Refractory inclusions were formed at high temperatures and are a very diverse group of materials, roughly divided into two categories: Ca-Al rich inclusions (CAIs) and amoeboid olivine aggregates (AOAs). They are the oldest known solids in the solar system, some of which have formed directly by condensation from the proto-planetary nebula, while others have formed by melt and evaporation of other pre-existing solids. (MacPherson, 2014; DeMeo et al., 2015) Chondrules however, most likely have formed as droplets composed of silicates and metals during short heading events in areas with a high concentration of dust, about 1-3 million years after the refractory inclusions. The matrix, in which they are embedded is so fine grained, that it is extremely susceptible to alteration of the parent body, but seems to have originally been made up mostly of crystalline and amorphous silicates. Most of the volatile materials contained within chondrites, like the entirety of the organic materials, all pre-solar grains and the water ice, that most chondrites must have accreted, are bound in the matrix. The population of chondrites is dominated by five groups which are defined by their physical characteristics, elemental compositions, and isotope ratios. Within the evolution of the parent bodies, they underwent different degrees of thermal modification and aqueous alteration, depending on the various thermal and chemical situations at hand. (DeMeo et al., 2015)

The extent of these alterations characterizes a meteorites petrologic type, which in turn influences the overall classification. A chondrite that was either unaffected by aqueous alteration or thermal metamorphism has a petrologic type of 3. The petrologic types 3-6 reflect an increasing share of thermal metamorphism, and 3-1 have increasing extent of aqueous alteration. A meteorite's petrologic type is usually given after its chemical group. The recognized chondrite classes are Enstatite (E), Rumuruti (R), Ordinary (O), Carbonaceous (C) and Kakangari (K). In the

Class	Groups	Characteristics
Enstatite (E)	EH, EL	Highly reduced, Metamorphosed type 3-6
Rumuruti (R)		Consists some OH-bearing Minerals, Metamorphosed type 3-6
Ordinary (O)	H, L, LL	Evidence for water activity
Carbonaceous (C)		
	CI, CM, CR	Aqueously altered types 1-3
	CO, CV	Evidence for water activity, Metamorphosed types 3
	CK	Evidence for water activity, Metamorphosed types 3-6
	CH, CB	CH, CB
Kakangari		

Table 3.1: Chondritic meteorite classification scheme, Credit: (DeMeo et al., 2015)

table below is a brief, summary of the classes with their sub groups and respective characteristics and petrological types.

3.1.2 Non-Chondrites

Non-Chondrites are, as their chondritic counterparts, mainly characterized according, to the physical and chemical properties of their components, like grain size, mineralogy, as well as their chemical and isotopic compositions. Since the main difference to the chondrites is that non-chondrites have undergone partial to severe melting, it is generally assumed that all non-chondritic meteorites (or their parent bodies) once were composed of chondritic materials that have evolved. Non-chondrites are generally divided into primitive achondrites, a type of meteorites that has on the one hand experienced severe metamorphism, but only relatively low degrees of melt extraction and partial melting, and differentiated meteorites who underwent intensive melting and partial to extensive differentiation. (DeMeo et al., 2015) The differentiated asteroids are further classified on the basis, of their iron contents into metal poor achondrites, stony-irons and irons. However, this classification has been in use since the 19th century, and a number of meteorites has repeatedly been misclassified, there are for example iron meteorites who show significant silicate inclusions, yet they are rarely described as stony irons.

Primitive achondrites are the link between chondrites and non-chondrites, since they sometimes even contain relic chondrules as small inclusions that have survived thermal metamorphism during their evolutionary process. However, up to this day they have not really been linked to any specific type of chondrites, with the exception of one ungrouped primitive achondrite, the so called tafassasset, who has chemical similarities to carbonaceous chondrites. (DeMeo et al., 2015; Gardner-Vandy et al., 2012)

Stony Irons are organized into two sub-types, the mesosiderites and pallasites. Mesosiderites are brecchias that are mainly composed of different silicate clasts mixed with iron nickel metal and sulfides. The amounts of iron and nickel are roughly equal. Pallasites are composed of iron and nickel metal/sulfide, that is intergrown with relatively coarse grained olivine and pyroxene crystals. Pallasites are again divided into three different groups, since they are most likely derived from at least three different parent bodies. Originally it has been assumed that pallasites formed at the border phase between the core and the mantle of large asteroids or even planetesimals, however Yang et al (2010) suggested that the main group of pallasites experienced cooling rates which would render that theory to be rather unrealistic. (Yang et al., 2010; DeMeo et al., 2015) Iron meteorites are generally divided into 14 different groups based on their chemical composition, however about 15% do not fit into any of these, and thus remain ungrouped. Each of the 14 groups belongs either to the magmatic, or the non-magmatic class. The main difference is that the intragroup chemical differences between the meteorites in the magmatic class can be explained by the fractionation between solid and liquid metal, which most likely occurred during the crystallization of planetesimal cores. The chemical differences in the non-magmatic class are harder to explain, but presumably they are either the by-products of failed core creations, or more likely impact generated.

3.2 Linkage between Asteroids and Meteorites

Much of what we do know certainly about asteroids, we learned from spectrophotometry conducted with telescopes. The principle is rather simple as a matter of fact, when we see an asteroid, we do not detect the sunlight as it has reached the surface of the body, but the surface acts as an imperfect mirror, reflecting better at some wavelengths. The reflection curve we see from Earth is loosely called the asteroid spectrum. Ideally, this would directly enable us to derive the elemental

Class	Characteristics
Primitive Achondrites	
Winonaites	Related to IAB irons
Acapulcoites and Iodranites	
Brachinites	
Achondrites	
Aubrites	Broadly basaltic compositions, Related to E chondrites
Ureilites	Contain aveins of graphite and diamond
Angrites	Basaltic compositions
HEDs	From 4Vesta
Howardites	Eucrite and diogenite breccias
Diogenites	Coarse pyroxene and olivine
Stony irons	
Mesosiderites	Impact breccias
Pallasites	Probably core mantle boundary material
Main group	Probably related to IIIAB irons
Eagle station group	Related to C chondrites
Pyroxene group	
Irons	
Magmatic	
IC, IIAB, IID, IIC, IIF, IIG, IIIAB, IIIE, IIIF, IVA, IVB	IVAs related to L and LL chondrites
Non-Magmatic	
IAB, IIE, IIICD	PIIEs related to H chondrites IABs related to winonaites

Table 3.2: Non-Chondritic meteorite classification scheme, Credit: (DeMeo et al., 2015)

abundancies, as every element has its own distinct spectral characteristics (wavelength dependent reflectivity). However, the current state of the art spectrophotometry does not support such ambitious attempts, not even for more abundant elements like Iron, let alone for the by far more interesting platin group elements, whose abundancies usually lie more in the parts per million range, making it even hard for scientists to find in meteorites. This is however not due to scientific limitations but the high prices for meteorite material. For a complete and accurate survey many grams are needed. Instead, we rely on unique wavelength-dependent absorption features that every mineral has. Since asteroids are usually rather far away, only a small amount of information arrives us. Additionally, asteroids usually rotate and tumble around faster than we can spectrally analyze a certain area, thus we get an overall spectrum of the entire surface viewed. Of course, that means that the asteroid spectra derived, are strongly dominated by the most abundant minerals, and those with the most extreme spectral features, making it hard to detect any other, whereas the other minerals present also make an identification of clear spectral features harder to achieve. This means that many asteroids can have rather different compositions and still look extremely similar as long, as they are dominated by the same minerals. On the other hand, this fact makes the taxonomic classification that much easier, if not possible in the first place, but it also makes it hard for asteroid miners to find out which materials could actually be mined on which body.

Thus, for now, meteorite mass spectroscopy studies pose the only possibility to derive, at least roughly, the compositions of asteroid taxonomic classes. The idea was simpl: analyze meteorites found on Earth in mass spectrometers, derive a low-resolution spectra of their surface, and then compare them to the taxonomic classes of asteroids.

Unfortunately, it is not that simple and the attempt to link the two different classification systems poses major difficulties. Asteroids suffer space weathering, changing their spectral features, but even if this would not be the case, and the asteroids would have an unaltered surface, they would be hard to compare, as meteorites suffer alteration during their flight through the atmosphere.

The best way to forge solid links between asteroid taxonomies and meteorite classes would be to observe the asteroid on its approach towards Earth. If we found them a couple of days or maybe even weeks before the impact, we could properly classify them with telescopes. After the impact, the meteorites could be at least partially recovered and thoroughly analyzed in laboratories. With only a few tens of such probes it would be possible to reliably tie the laboratory compositions to their spectral types. However, only one such asteroid has been found to date, 2008 TC3. The Apollo asteroid was classified a F/M type during his approach towards Earth and the meteorite turned out to be a very rare ureilite. Despite the fact, that a single case does statistically speaking not quite provide a qualitative prove, it

suffices to link the spectral type to at least one meteorite class. (Jenniskens et al., 2009; DeMeo et al., 2015)
With an estimated frequency of about a dozen similar sized objects impacting Earth every year (this estimation has a significant uncertainty, since it is based on only 12 known events), it could be well possible to decrypt the relationship between asteroids and meteorite classes for good. (Brown et al., 2002; DeMeo et al., 2015) Even though about two thirds will never impact on land, because two thirds would approximately dump in the ocean, and half of the rest would probably fall into areas where they cannot be recovered, their fireballs could be observed as they enter the atmosphere, and a few a year may be retrievable. (Jenniskens, 2007; DeMeo et al., 2015) The next best solution would be to send space probes to well-known asteroids with complete taxonomic classifications for a rendezvous mission returning samples back to earth for laboratory analysis, as happened with the Hayabusa mission which will be reviewed in greater detail in the next chapter. But not only the material brought back to Earth is of high interest. Spacecraft are also able to obtain data that are very hard or simply impossible from Earth to obtain. This includes high resolution images, reflectance spectra of different lithologic units, bulk densities and bulk elemental compositions. To find meteorite parent bodies, and in consequence forge links between the different classes, bulk elemental compositions are probably the most valuable information that can be obtained because it can be directly compared to meteoritic bulk compositions obtained on Earth. (Jenniskens et al., 2009; DeMeo et al., 2015; Jarosewich, 1990; Burbine et al., 2002) These space missions however, currently cost hundreds of millions, making this approach a costly lesson.
With these limitations science had to become more creative to try and establish possible relationships. Some proposed that the relative abundancies of asteroids and meteorites should be at least considered, since the most common asteroid types should be also the source of the most common meteorites found. But the abundancy of certain classes is not nearly as important as the pathways that meteorites can take to Earth. Thus, the search for resonances and the most common asteroid classes, not in vicinity of Earth but at the source regions, the areas of dynamic chaos went on. (Burbine et al., 2002; DeMeo et al., 2015) A major advance towards interpreting the relationships is the ever-growing understanding of the various mechanics that work in the main belt, as in vicinity of Earth. (DeMeo et al., 2015) For asteroids that approach closely to Earth, radar measurements can be used to improve the scarce knowledge of their surface structure, in the hope of finding clues. One way was to try and compare the spectral features, to try and compare mineral abundancies, however that is very hard to do with low resolution spectra, considering that there is an overall similarity between many different taxonomic type (at least in respect to the quality of most spectra at hand). This is still one of the most often used methods to argue for a proposed linkage, however they are

not quite robust since even in the most similar spectral features, there are major discrepancies. Thus, instead of directly matching the entire spectra, the shapes of the curves were compared, focusing only on the most dominant features of the most dominant minerals. (DeMeo et al., 2015) Pyroxene and olivine are present in most meteorite types, and both have distinctive absorption features in the near infrared, making them easy to be identified on asteroids, as that lies exactly within the range of wavelength that asteroids are classified with. Olivine has an asymmetric absorption feature at one micron. Most pyroxenes have two absorption features at one and two microns. Laboratory studies however have shown that the exact locations and strength of the absorption features can vary as a function of mineral chemistry. Plagioclase, which is found mainly in chondritic meteorites is harder to detect in asteroids due to the weakness of its 1.25 micron absorption feature. The presence of iron is due to its lack of distinct absorption features hard to determine and usually just makes the overall asteroid spectrum more slope. (DeMeo et al., 2015)

By now, especially with respect to the findings of the Hayabusa mission, it is abundantly clear that at least a fraction of S-complex asteroids are the source of ordinary chondrites, and that HEDs are most commonly associated with Vesta. But for most taxonomic types the associations to meteorite classes are by far less robust and usually rely heavily on indicators more than on hard evidence. It is generally understood that some of the C-complex asteroids are likely linked to some subtypes of carbonaceous chondrites (probably CM). (Jenniskens et al., 2009; DeMeo et al., 2015) E-type asteroids have been associated with enstatite chondrites, or achondrites, which are compositionally similar and most likely related. M-types are proposed to be linked with metallic meteorites. A-types with pallasites or olivine rich achondrites, and L-types with CAIs. However, these links are highly speculative and evidence remains to be provided. (Cloutis and Gaffey, 1991; DeMeo et al., 2015) Despite most of these associations being disputable at best, meteorite elemental abundances give a good impression about which quantities of materials can be expected once we reach the asteroids.

Chapter 4

Missions to Asteroids

4.1 NEAR Shoemaker

NASAs Near-Earh Asteroid Rendezvous-Shoemaker was the first launch of NASA's Discovery program, and the first space mission ever to perform a in situ characterization of the surficial chemical elements present. It visited the second largest near Earth asteroid S-type 433 Eros in 2000 after about 4 years of travel time. Eros is an asteroid from the Amor family and has a close period orbit of one year, and an orbit that is typical for its family, never quite reaching Earth's. NEAR-Shoemaker was also the first mission to orbit an asteroid, which it did for over a one year period, and the first to touch-down on an asteroid's surface (February 12th 2001). The mission's goals were to provide data about the asteroids surficial composition, mineralogy, morphology, internal mass distribution, magnetic field and overall physical properties. The probe was designed by the Johns Hopkins University applied Physics Laboratory and costed 124.9 million dollar, resulting in a total mission cost of 224 million dollar.(Farquhar et al., 1995; Veverka et al., 2000; Zuber et al., 2000; Elvis, 2013)

4.2 Hayabusa

Developed by the Japan Aerospace Exploration Agency (JAXA), Hayabusa is probably one of the most famous missions to an asteroid so far. It was a sample return mission to 25143 Itokawa, a small S-type Apollo asteroid of about 550 ± 180 meters. Hayabusa was launched in 2003 and arrived at its destination in 2005, where it conducted measurements of the shape, spin topography, color, and composition, and studied its evolutionary history. It carried the detachable minilander MINERVA, which unfortunately failed to reach the surface. Hayabusa itself however did not fail, and touched-down two times on the asteroids surface, lifting off, and capturing regolith grains, bringing them back to Earth on June 2010. Extensive Laboratory studies found that these few micrometer sized grains were indeed asteroid regolith, not only captured dust and finally settled the dispute about whether, or not S-type asteroids were the parent bodies of ordinary chondrites. These findings are particularly relevant, because they opened the doors for further study and help greatly in understanding the extent of surface alteration by space weathering.(Fujiwara et al., 2006; Nakamura et al., 2012; Elvis, 2013)

4.3 Hayabusa2

After the great scientific and prestigious success of the Hayabusa mission, JAXA decided to launch a second sample retrieve mission to an asteroid. This time their target is a C-type Apollo, the asteroid 162173 Ryugu with an estimated size of 980 ± 29 meters and an orbital period of 1.3 years. Hayabusa 2 was launched on Dezember 3rd, 2004, and is expected to reach its destination in July 2018.Once there, it will first survey the asteroid for a year and a half, and depart again in December 2019 hopefully bringing some regolith samples with it back to Earth. As the first Hayabusa mission it is equipped with a mini-lander. It was built by the German Aerospace Center in co-operation with the French space agency CNES, and is called MASCOT (Mobile Asteroid Surface Scout). After conducting surface studies, it will be able to lift off again by itself to reposition itself for further measurements. Hayabusa 2 is also equipped with the Small Carry-on Impactor that will penetrate the uppermost layers to form a crater and expose fresh unweathered asteroid material to observation by the on-board equipment. (Ishiguro et al., 2014)

4.4 Osiris-Rex

The Origins-Spectral Interpretation-Resource Identification-Security Regolith Explorer is the first NASA mission that will return samples from an asteroid back to Earth. It was launched on September 8th 2016, spending the following 3 years travelling to its destination, the primitive B-type (sub category of C-complex) Apollo Near Earth Asteroid 101955 Bennu. The mission goals are to conduct a comprehensive mapping of the asteroid's surface, doing in situ analysis of the samples, measuring its orbit deviation caused by the Yarkowsky effect, and comparing observations at the asteroid to ground-based observations. The mapping itself is expected to take about 6 months. Then, the spacecraft will pick a location from where its arm will take a sample of B-type regolith. It will be of outmost interest to asteroid miners, as it will be the first try to perform an in situ mapping of the manifestation of space weathering on an asteroids surface. (Lauretta et al., 2015)

4.5 AIDA

The Asteroid Impact and Deflection Assessment mission, is a proposed joint venture mission concept among NASA, ESA, the Observatoire de la Cote d'Azur (OCA) and the Johns Hopkins University Applied Physics Laboratory. If financed and conducted, it would be the first demonstration of kinetic impact technique to change the motion of an asteroid in space. The dual mission concept would involve two independently operating spacecraft: NASA's Double Asteroid Redirection Test (DART), and ESA's Asteroid Impact Mission (AIM). The goal of the mission would be to test a technology to prevent a PHO impact on Earth, by measuring the effects of the kinetic impact of DART on the motion of a 150-meter sized asteroid. The target asteroid is the secondary body of 65803 Didymos, a binary NEA. AIM would arrive at the binary asteroid before DART and perform high resolution observation of the surface conditions, as well as measurements of the densities, masses, and shapes of both bodies. DART would later deliberately crash itself into the secondary body with an approximate speed of about 6km/h, while AIM closely observes and investigates the direct effects of the impact itself, possible mass or momentum transfers between the two bodies, the crater formation, the redistribution of the ejected mass, and thereby deliver constraints to the inner structure of the asteroids. If approved, AIM and DART would have to start in October and December 2020, arriving in May and October 2022 11 million Kilometers away from Earth. The findings of this unique double-mission would greatly help in averting terrible asteroid impacts in the future. (NASA, 2017a)

Chapter 5

Space Weathering

Space weathering is a term used for a variety of processes that influence the observable physical, chemical and mineralogical properties of the surface of atmosphereless bodies in space. As terrestrial weathering (ie. erosion or chemical weathering), space weathering represents harsh conditions that can destroy molecules, thus not only making it hard for us to properly identify surface compositions, but also posing a major threat for any organic materials that are exposed to it. (Domingue et al., 2014) Generally alteration by space weathering is strictly tied to the exposure of a surface to its space environment. The space environment includes exogenic agents such as solar wind electrons and ions, solar photons, cosmic radiation, and impacting debris from other comets and asteroids called micrometeorites. Thus, the magnitude of chemical and physical alteration largely depends on the flux, energy, rate of impact, and composition of the impacting particles and the surface itself. Also, a pre-existing magnetic field could influence the alteration, yet this is mostly limited to larger bodies like Mercury, as most asteroids could not sustain a magnetic field. (Domingue et al., 2014)
Most of what we know to date about the various mechanisms behind space weathering and its effects on the spectral appearance of the surface composition has come from the combined studies of lunar samples and the remote sensing of the moon. However, unlike the moon with its orbit around the Earth, thus more or less the same distance from the sun all year long, asteroids do not dwell in the same space environment for most of their time. They span a considerable range of heliocentric distances instead, and many of the factors that influence the alteration change with heliocentric distance. Therefore, while the processes of space weathering themselves should not differ too much between the moon and asteroids, the magnitude most definitely does. (Domingue et al., 2014)

5.1 Space weathering mechanisms

Generally, the mechanisms of space weathering are divided into two major groups: the physical processes, and the radiative processes. Despite the various processes will be reviewed separately, it should be kept in mind, how each of them affects

the others in understanding exosphere formation, and surface modification.
The reason why lunar surface samples are reviewed in this chapter rather than meteorites, is that when a meteorite crashes down on Earth its surface layers are largely altered or evaporated away during its flight through the atmosphere, and the various inclusions inside the meteorites could have formed from other processes independent from space weathering, whereas lunar samples are guaranteed upper most surface layers, concluding in a higher overall chance that any alterations are due to space weathering.

5.1.1 Physical alteration processes

Regolith formation is most likely the product of the communication of the asteroids surface bedrock with local boulders by repeated impacts. While larger impacts dominate the alteration of the physical properties of asteroids by excavation, fracturing, and comminution of bedrock, smaller impacts of the scale < 1 cm in diameter, works on the soil grain scale. There are four critical physical alteration processes based on micrometeorite bombardment playing a major role in the evolution of surfaces: Gardening, melt and vapor production, chemical reduction and devolatilization, and preferential processing by size and composition. The specific magnitude of each effect depends on the impactor flux, impact velocity, and by the target temperature, composition, and respective material strength.

5.1.1.1 Gardening

Gardening is, as the name suggests, the continuing process of excavation and burial of surface material by various sized impacts. As micrometeorites impact the surface of an atmosphere-less body, they form small craters, cracking up and ejecting surface material. At least some of the ejected material later falls back to the surface and mixes with the remnant materials of the micrometeorite and the freshly exposed subsurface asteroid material. Gardening is thought to one of the most important processes of space weathering, as it not only tends to compositionally homogenize the surface, but also by being the only supplier of fresh and un-weathered materials to the surface, it affects and limits other space weathering processes like the efficiency of impact vaporization. (Domingue et al., 2014)
The exact efficiency of the overturn rate thereby largely depends of the ratio between the mean impact velocity and size, as these are the dominant factors for ejection energy, and the gravitation of the target body, which determines the share of the ejected material that is reaccreted. For example; on the moon, the overturn of a 1cm thick layer of regolith has been argued to take some 10^6 years (Heiken et al., 1991; Domingue et al., 2014), on Mercury however due to a higher impact flux, and stronger gravitational accretion that is assumed to make up for the higher impact velocities, the same 1cm thick layer has been postulated to be overturned

within some $1.5 * 10^5$years. (Killen et al., 2008; Domingue et al., 2014) Since most asteroids are rather small it is assumed that the gardening rate for most asteroids is dominated by excavation of mass loss, and only the larger asteroids like Vesta or Eros can sustain a considerable amount of regolith formation. (Domingue et al., 2014) Since the mean impact velocity and flux of micrometeorite bombardment change with heliocentric distance (at least the mean size of the impacting micrometeorites is expected to be rather constant between 0.1 and 1 AU) (Domingue et al., 2014), the overturn rate for NEAs can be expected to be lower, while the mass loss should be a bit higher than for main belt asteroids. Also, with the low average asteroid gravitation, the surface material strength becomes a more important factor in the gardening rate, as most of the material ejected is expected to be lost into space. Thus, the physical properties of an asteroid, whether it is differentiated or not, the chemical composition of the uppermost layers, and whether it has been fractured before, govern the gardening on asteroids more than on the moon. However, due to poorly understood fine grained regolith behavior under microgravitational conditions, the large range of asteroid sizes, heliocentric distances, and compositions there have so far been no suggestions for asteroid overturn rates.

5.1.1.2 Melt and vapor production

Melt and vapor production by impact depends on the composition of both, the impactor and the target, as well as the impactor mass and velocity. When a micrometeorite impacts an asteroid's surface, most of its kinetic energy is transformed in thermal energy, with the rest being distributed amongst the following ejection and the target body itself. Since there is no kind of atmosphere nearly dense enough to slow down the approaching particles by friction, the entirety of the heat is focused directly at the impact area. It has been showed that varying the impact velocity only by a factor of 2, influenced the generation of impact melt by a factor of 3 and the vapor production even by a factor of 4-5. (Cintala, 1992; Domingue et al., 2014) Therefore, temperatures high enough to evaporate volatiles, and melt more robust materials bound in the surface, are not uncommon. On lunar and mercurial surface, especially the generation of natrium exospheres (Thin atmosphere-like volumes that surround a celestial body where molecules are gravitationally bound, but where the density is so low that they cannot behave as a gas by colliding with each other) is one of the most important features of vapor production. It has served science to calculate the impactor flux for mercury, as the lunar exosphere has been compared to the more prominent one of mercury. (Mouawad et al., 2011; Domingue et al., 2014) On asteroids the vapor production does, again due to the lower gravity, only produce exospheres to a far lesser degree, but generally make for a higher mass loss and volatile depletion of the asteroid surface. However not all, of the vapor produced ever leaves the asteroid surface. The temperatures produced at high velocity impacts melts silicates producing glass within the regolith, and some of the vapor resublimates as soon as it comes into contact with nearby regolith particles which haven't been heated by the impact, and thus still have the initial temperature of the asteroid surface, which of course always depends on whether it is on the noon or the night side, and the current heliocentric distance, but is usually rather cool. The resublimation leads to the particles being coated in patinas, creating a repository for the volatile elements released during the impact, and even leads to the formation of additional glass. (Domingue et al., 2014)

In lunar surface soils, two types of glass have been identified. They are defined by differences in their shape and surface texture. The first type of glass is shaped in rather regular spheres or ellipsoids with smooth surfaces. These spheres are mostly free of clasts (inclusions of mineral fragments), and are chemically homogeneous. (Delano, 1986; Hörz and Cintala, 1997; Delano, 1986; Domingue et al., 2014; Papanastassiou and Wasserburg, 1971) They are thought to be either of volcanic origin, or more likely produced by micrometeorite impact on surficial crystalline rock. The second type of glass is shaped rather irregularly and often jagged and vesicular. The inclusions it this glass make their chemical composition inhomogeneous. It is usually found in agglutinates, a type of small glassy breccias that makes up the major component of surface regoliths. Agglutinates are thought to form by the following impact process: (McKay, 1991; Hörz and Cintala, 1997; Domingue et al., 2014)

A high-velocity micrometeorite impacts a surface, the soil of which contains previously implanted solar wind particles like hydrogen and helium. Surface grains are melted by the high temperature produced by the impact and forms glass, releasing the implanted solar wind particles. The released hydrogen reacts with the FeO that was in the soil grains and reduces it to metallic iron by binding the Oxygen into water molecules. Most of the produced water is thought to escape from the glass, as there has been no sign of H_2O within Agglutinates retrieved from lunar regolith. (Domingue et al., 2014; Taylor et al., 1995) The escaping vapor of volatiles and solar wind particles bound in the soil, and the freshly formed water, leaves vesicles behind. The Fe that has been reduced forms nanometer sized iron droplets called nanophase iron $npFe^0$, that are stored in agglutinate inclusions together with soil particles engulfed within the molten glass. The solar wind particles bound within the soil particles engulfed by the molten glass most likely escape the particles by thermal excitation, however are trapped within the cooling glass. (Domingue et al., 2014; McKay, 1991) Since there is, as mentioned, no water within these agglutinates, whereas the $npFe^0$ is, it has been argued that the reducing agent may not be the hydrogen after all but the Carbon interacting with solar winds. (Domingue et al., 2014; Taylor et al., 1995)

5.1.1.3 Material reduction and devolatilization

Material reduction and devolatilization is the main source for the spectral changes due to space weathering. The $npFe^0$ inclusions, that are a direct result of the reduction. These $npFe^0$ particles occur in rims surrounding individual grains, or in agglutinates.(Keller and McKay, 1993; Domingue et al., 2014) They have two outstanding characteristics. Firstly, they usually consist of relatively pure iron, which is remarkable because usually iron present in asteroid and lunar regolith is usually only found in combination with large shares of Nickel and Cobalt. Secondly, they are extremely fine grained, suggesting that the reduction occurs only limited, enhancing the theory that they derive from singular reduction when solar wind implanted hydrogen happens to 'meet' an oxydated iron. Ferromagnetic analysis showed that most nanophase iron is in the size-range of only 3-10 nm, meaning that they are not always visible for optical microscopes.(Keller and McKay, 1993; Domingue et al., 2014; Morris, 1976) The nanophase iron particles seem to be distributed by size, the smaller ones of about 3 nm in diameter are usually found in the rims coating surficial regolith grains, whereas the larger ones of about 7nm in diameter, are found as components of agglutinate inclusions. (Domingue et al., 2014; Keller and Clemett, 2001) Also, the nanophase iron in rims is shows higher abundancies within finer soil samples, which makes sense, as the formation of it is a surficial process and smaller grains have a higher surface/volume ratio. Laboratory examinations of Itokawa samples from Hayabusa have shown that areas with a higher concentration of $npFe^0$ are surrounded by zones with a relative iron depletion, enhancing the theory that nanophase iron is formed in situ.(Domingue et al., 2014)

Figure 5.1 Shows Agglutinates within meteorites.

5.1.1.4 Preferential processing

Preferential processing by size and composition is important, since different minerals tend to behave differently under the same conditions, in response to fracturing and thermal heating. Therefore, rocks with a lower material strength will tend to be fractured to smaller grains and boulders than those with a physically more robust chemical composition, and silicate minerals with a lower melting point will contribute relatively more to the formation of glasses like agglutinates. This is proven by lunar soil samples that show that feldspar has a higher ratio amongst the smaller sized fractionations than in the larger ones, compared to its overall abundancy in lunar regolith.(Papike et al., 1982; McKay, 1991; Domingue et al., 2014) Also, minerals that occur as very small grains within lunar surface rocks in the first hand, are concentrated in the finer regolith, after they have been fractioned. This is an important statement, as the $< 45\mu m$ diameter grains dominate the spectral reflectance properties, as their surface is relatively large compared to

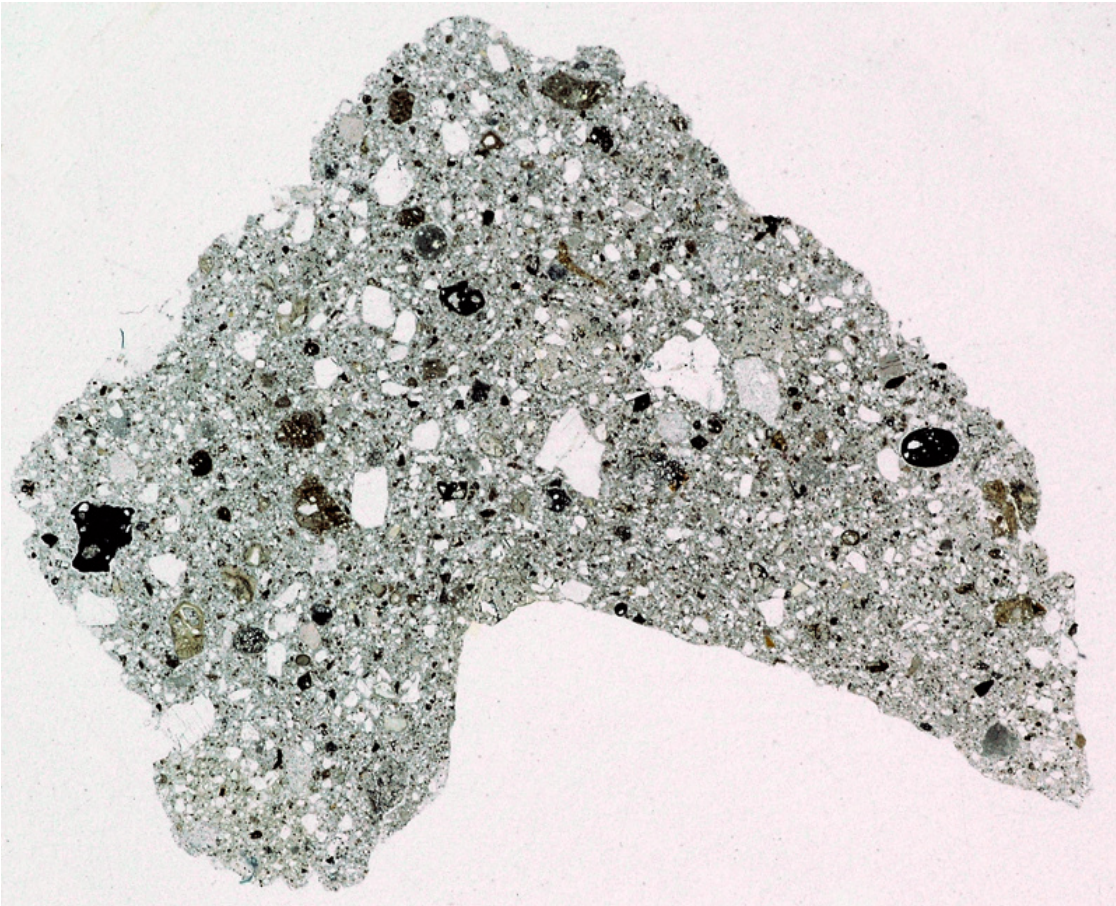

Figure 5.1: Agglutinates within Meteorites, Credits: (Korotev, 2015)

their overall mass abundancy. (Pieters, 1983; Pieters et al., 1993; Pieters and Englert, 1993; Domingue et al., 2014)

The composition dependent contribution to melts, is called differential melting, which is not to be confused with differentiation of asteroid bodies. It is important in the processes around the production of glass, especially the agglutinates, and is vital in order, to understand some of the observations made when studying lunar soil samples. The concentration of agglutinates for example increases, with decreasing grain size of lunar regolith, and their compositions seem to form some mixture between bulk highland soil compositions, with a high concentration of basaltic components like FeO or MgO, and mare soil compositions, that are depleted in TiO_2.(Taylor et al., 2001, 2010; Domingue et al., 2014) It has been argued that these observations can be explained by a mixing of mare and highland soils, in combination with a differential melting sequence. For example: glass is by far more abundant in the lunar soil, than plagioclase, which in turn is more abundant than pyroxene or ilmenite. Since none of these materials are native to the lunar soil, and can only have been formed under space weathering influence, it is obvious that the conditions necessary for the processes involved in forming glass are more easily met than those for the formation of plagioclase.(Pieters and Taylor, 2003; Domingue et al., 2014) Yet not only the various melting points of the minerals at hand cause fractionations of relative abundancies, but also the isotopic composition itself varies amongst lunar soils. Especially the depletion of volatiles, elements such as hydrogen, oxygen, sulfur and different alkali metals, that escape their chemical boundaries under impact driven thermal heating, show signs of fractionation by isotopes. The lighter isotopes of these elements tend to escape gravity more easily than the heavier ones, that settle back down on the surface to form patinas. This leads to an enrichment of the lunar surface soil in ^{18}O and ^{30}Si relative to their abundancies in lunar rocks. (McKay, 1991; Epstein and Taylor Jr, 1972; Domingue et al., 2014) The relative abundancies further showed that oxygen seems to escape more easily compared to silicons during the fractional vaporization process. This further contributes to a reduces environment, and higher production efficiency of nanophase iron. (McKay, 1991; Domingue et al., 2014) Further, an increased concentration of other volatiles such as Zn, Ga, Ge, Cd, Sb, Te, and Hg can be observed within the finer fractions of surface grains. This is probably due to the higher surface to volume ratio, leading to a relatively larger amount of volatiles re-sublimating on grains compared to larger boulders. (Krähenbühl et al., 1977; Domingue et al., 2014) These processes will also occur on asteroids. The NEAs suffer the relatively same impact parameters, as their heliocentric distance, which is the dominant factor for flux and velocity distribution, which in turn define the impact energies over a certain time-period, does not differ to much from the moons. The main belt asteroids environment offers a smaller meteorite flux and less relative velocities, which in combination with a cooler surface should derive in an overall smaller amount of thermal energy available for differential melting and fractional vaporization. However, for both, near Earth and main belt asteroids, the by far lower gravity should allow for all volatiles to escape more easily, and enhance ratio of lighter/heavier isotopes lost, and therefore lead to a more extreme depletion of surface volatiles, and a stronger fracturing by isotopes.

5.1.2 Radiative processes

Atmosphere-less are are not only bombarded by micrometeorites, but also by solar wind ions, that mature the surfaces. On asteroids, with their general lower effectiveness of mechanical surface alteration that were reviewed in the previous sections, compared to the lunar space weathering, radiative space weathering is considered a major agent. To comprehend the role of these processes, a deeper understanding of the chemical, physical and mineralogical changes induced by the communication of radiation and surface materials is necessary. Therefore, we now examine the surface effects resulting from ion implantation, physical and chemical sputtering, thermal desorption, and desorption induced by electronic transition. (Domingue et al., 2014)

5.1.2.1 Ion implantation

Ion implantation results from the bombardment by solar wind or magnetospheric (only to a small degree for asteroids, as they usually do not enter any major body's magnetosphere) ions. It happens, when a collision between a solar wind ion, and a regolith grain, results in the capturing and accommodation of said ion within the grain's matrix. It has been demonstrated that solar wind protons at keV energies can implant themselves in surface grains to a depth of up to 10nm. Ions with a higher energy level such as cosmic rays with over 50 keV can bury themselves even deeper in the grain lattice structure. Still, that means that implantation is an effect that only works on the uppermost layers of surficial soil compared to the physical weathering processes. (Hofer et al., 1991; Domingue et al., 2014) On their way through the lattice structure, these ions produce defects in the lattice structure, that provide additional conduits and thereby enhance the diffusion of volatiles from within the grain to its surface. This enhances desorption processes creating opportunities for absorption of atoms by the exosphere. Evidence for such implantations is found in lunar regolith samples which have been exposed to radiation, that show the presence of hydrogen captured by surface grains. Hydrogen is however only abundant in the top layers of the surface to a depth of some 50 nm. (DesMarais et al., 1974; Epstein and Taylor Jr, 1975; Crider and Vondrak, 2003; Domingue et al., 2014)
The bombardment of solar wind protons begins with the implantation of a pro-

ton within the surface of a grain. There, it reduces an atom in the outer layers of the surface by picking up an electron to form a hydrogen atom. The chemical reduction results in the production of OH, H_2O, and $npFe^0$, as was explained in the chemical reduction section. Thereby, it damages atomic bonds, opening them up for adsorption of gaseous exospheric molecules such as H_2O. In lunar samples, the content of hydrogen within regolith depends largely on exposure age, maturity, and the temperature of said soil. (DesMarais et al., 1974; Crider and Vondrak, 2003; Domingue et al., 2014)In very mature equatorial lunar soils, hydrogen has a concentration of 50-75 parts per million, whereas equally mature soils of higher latitudes (thus colder) shows an abundancy of 150-175 parts per million. This implies a steady state between the rates of production and release of H_2 is achieved, leading to a steady soil content of hydrogen. Ion implantation is a steady supplier of hydrogen in the uppermost regolith layers, however there are several mechanisms that can lead to the release of H_2. While the release by thermal desorption is thought to make a rather small fraction of the overall loss of hydrogen, sputtering and vaporization are the dominant processes. Vaporization mostly depends on the impacts of micrometeorites, as this is the only supplier of sufficient thermal energy, whereas sputtering will be reviewed in the next sections. (Crider and Vondrak, 2003; Domingue et al., 2014)

While the mechanisms themselves do not change between asteroids and the moon, the general conditions differ extremely. The flux of solar wind declines with heliocentric distance following the spherical radiation transport equations, leading to a smaller rate of ion implantation for main belt asteroids, than for NEAs or the moon. However less solar wind flux also diminishes the already small influence of thermal desorption on the release of volatiles. Of course, the temperature of a body's surface depends not only on the radiative flux, but also on albedo, which is considerably smaller for C-complex asteroids than on the moon, whereas S-complex asteroids have a comparable to slightly higher albedo. Also, regolith porosities have a strong influence on the capture of ions and the release of hydrogen. Overall there should be at least a bit less hydrogen stored in the surface areas of asteroids, than there is on the moon.

5.1.2.2 Physical sputtering

Physical sputtering is much like ion implantation a process, a process which involves the collision of solar wind with surface grains. However, this process requires higher energies than ion implantation, and results in the release of single atoms from surface molecules, changing its chemical composition. Basically, the solar wind energizes the atoms it interacts with, enabling them to overcome the binding energy of their molecule. Physical sputtering acts only of the upmost atomic layers, and contributes to the exosphere, that is otherwise sustained by impact vaporization and photon-stimulated desorption. Therefore, a bodie's exosphere reflects the elemental composition of the surface, though not its relative elemental abundancies. (Johnson et al., 2002; Killen et al., 2008; Wurz et al., 2007, 2010; Domingue et al., 2014) All elements, and molecules react differently to impacting high energy radiations, leading to certain minerals being more vulnerable to sputtering. Some of the highest sputtering yields, are those of H, O, and OH, which means that ongoing physical sputtering will eventually deplete the uppermost surface atomic layers of these elements, leaving it enriched in elements with a lower sputtering yield as for example Ti and Fe. (Killen et al., 2008; Domingue et al., 2014) Any calculations considering physical sputtering rates however have to take into account that a different mineralogical composition and mineral matrix of the surface varies the various sputtering yields. It has been proposed that physical sputtering also produces amorphous rims found on fine grained surface regolith by reducing, and disordering of the topmost mono-layers, and is therefore another way of reducing Fe^{2+} to produce nanophase iron on the surface. (Killen et al., 2008; Domingue et al., 2014) The modification rate by physical sputtering of surface grains depends largely on several variables, like the surface composition, the gardening rate, the rate of diffusion of particles from inside the grains to its surface, the composition, flux, and energy of incoming solar wind, and the volume diffusion rate of the regolith. Physical sputtering has been argued to play a major in the surficial depletion of volatiles that have a high sputtering yield. Due to physical sputtering and micrometeorite impact driven vaporization taking place simultaneously, it is hard to tell which process accounts for what exact fraction of depletion, yet models show that they contribute overall comparably, at least in the same order of magnitude, with the exception of those elements with a low sputtering yield like Na, Al, Si, P, S, Fe, and Ti. (Wurz et al., 2010; Domingue et al., 2014)

5.1.2.3 Chemical sputtering

Chemical Sputtering releases atoms and molecule grains not by energetic excitation, but simply by reacting with them. It depends on the implantation of solar wind ions, predominantly protons, which react with the surface minerals, as already mentioned in the section about ion implantation. Chemical sputtering is thought to produce elemental sodium, hydrogen, hydroxyl and water, which are then removed from the surface to the exosphere by various processes, and are later lost to photo-ionization, and radiation pressure, overcoming their gravitational boundaries. (Potter, 1995; Crider and Vondrak, 2003; Domingue et al., 2014) Especially the formation of hydroxyl by bombardment of oxides with ions, has already been proven by laboratory experiments. (Gruen et al., 1976; Siskind et al., 1977; Zeller et al., 1966; Domingue et al., 2014) It has been argued, that the chemical sputtering rate of water by solar wind protons on the moon is somewhere near 0.01 molecules/ion. As already mentioned in the previous sections,

there are a range of chemical reactions taking place within the micrometeorite impact produced melt, and vapor that later cools down to form patinas around surface grains, or agglutinates. The production of nanophase iron works by the following reaction $2H + FeO \rightarrow Fe^0 + H_2O$. A reaction to produce water and sodium by chemical sputtering of sodium bearing minerals has been proposed to be $2H + Na_2Sio_3 2Na + SiO_3 + H_2O$, producing twice the amount of sodium than water. (Potter, 1995; Domingue et al., 2014)
It has been argued that the solar wind radiation does not in fact produce solely H_2O, but under certain conditions instead tends to form H_2 and OH^-. (Starukhina, 2006; Domingue et al., 2014) This OH radical, could serve in the further reduction of surficial Fe^{2+} to Fe^0, removing O^{2-} from the regolith, and thereby help to increase the production efficiency of nanophase iron in agglutinates and patina rims during micrometeoridal impacts. (Domingue et al., 2014) Despite lunar regolith samples being dominated by anhydrous minerals, spectral reflectance observations of the lunar surface have shown that H_2O and OH are both ubiquitous. (Papike et al., 1991; Domingue et al., 2014) The strength of the water and hydroxyl spectral features varies with time, indicating that they are really produced in situ by interaction with the fluctuating solar wind, as was speculated. (Vilas et al., 2008; Clark, 2009; Pieters et al., 2009; Sunshine et al., 2009; Domingue et al., 2014)
Killen and Sarantos (2013) have calculated an upper limit to the production of water on the lunar surface to be some 500 $molecules/cm^3$, which can be expected to be rather similar on asteroid surfaces due to the similar thermal conditions, with the incoming solar wind flux being the only really important difference, depending on the exact location of the body in the solar system.(Farrell et al., 2013) The lower gravitation would of course also account for a lower overall threshold of water and hydroxyl of an asteroids surface compared to the moon's, yet the exosphere is not really a long-living, but rather a permanently replenished phenomenon, thus the small mass should not be too much of an issue. These were only the best known two examples of a large variety of chemical reactions induced on asteroid surfaces by sputtering, and much remains to be examined.

5.1.2.4 Electronic transitions induced desorption

Electronic transitions induced desorption of atoms is a physical surface phenomenon that is a result of interactions between molecules and incoming solar wind electrons (ESD) or photons (PSD), leading to the removal of ions, atoms and molecules from the bulk composition to a gaseous or liquid phase contributing to the generation of an exosphere via electric transitions. ESD typically involves the inelastic scatterings of low-energy electrons (between 4 and 50 eV) created by high-energy incident radiation. These extremely complicated multi-electron excitations usually occur more frequently at the site of defects in the uppermost lattice layers. PSD is generally a single-electron transition triggered by photons from the visible to ul-

traviolet radiation, but can also happen by interaction with higher energy photons like X-rays with a much higher penetration depth resulting in a core-level atomic transition. (Domingue et al., 2014)
The exact ratio of neutral material versus ions desorbed by such electronic transitions usually depends on the initial chemical state of the surficial grains, and the incident energy. The desorption rate of neutrals is orders of magnitude higher relative to ions, when conducted on metallic surfaces or other materials with a low-energy excitation (sub-band-gap), as are extremely common of X-complex asteroids. The desorption rate of ions increases for mineral surfaces, oxides and any material subjectable to Auger-decay (an effect where an atoms inner-shell vacancy is filled with an electron of a higher energy level, resulting in the release of energy via either a photon or another electron of said atom), for example on C-complex asteroids. (Domingue et al., 2014)
As mentioned before, electronic transitions induced desorption preferentially targets defect atomic layers. This is due to the fact, that when an atom is missing, the molecules at hand have a critical energetic imbalance, either excess or deficit charge. This differential charge distribution and reduced repulsion energy leads to the localization or self-trap of an excitation. While these excitations move smoothly through well-structured crystalline materials, this energy flow stops as soon as defects are encountered, thus trapped. The trapped energy then leads to the breaking of bonds between atoms and molecules and therefore frees the target and desorbs it.(Domingue et al., 2014; Killen et al., 2008; Lammer et al., 2003; Killen and Ip, 1999) Such defects are a side effect of different other space weathering mechanisms and therefore ubiquitous on asteroid surfaces, their abundancy depending on the composition of the surface. Generally, ESD and PSD can remove most atoms and molecules from terminal sites within the uppermost lattice layers of the surface, yet preferentially target certain species, depleting the minerals of alkalis, hydrogen and oxygen, usually leaving behind greater concentrations of Fe and Mg than initial composition, sometimes reduced and thereby further contributing to the formation of nanophase iron. The desorption yields of both ESD and PSD largely depend on the chemical state, composition, temperature and physical characteristics like porosity (which determines the amount of desorbed atoms being caught by other grains, and overall loss of material to the exosphere). Further, PSD shows a dependency on latitude. (Domingue et al., 2014; Killen et al., 2008; Lammer et al., 2003; Killen and Ip, 1999)

5.1.2.5 Thermal desorption

Thermal desorption involves the removal of adsorbed atoms through heating. It should not be confused with the impact driven vaporization of surficial material, which can also result in the loss of said vaporized molecules. Thermal desorption is a more 'subtle' process that utilizes heat to increase the volatility of contaminants and

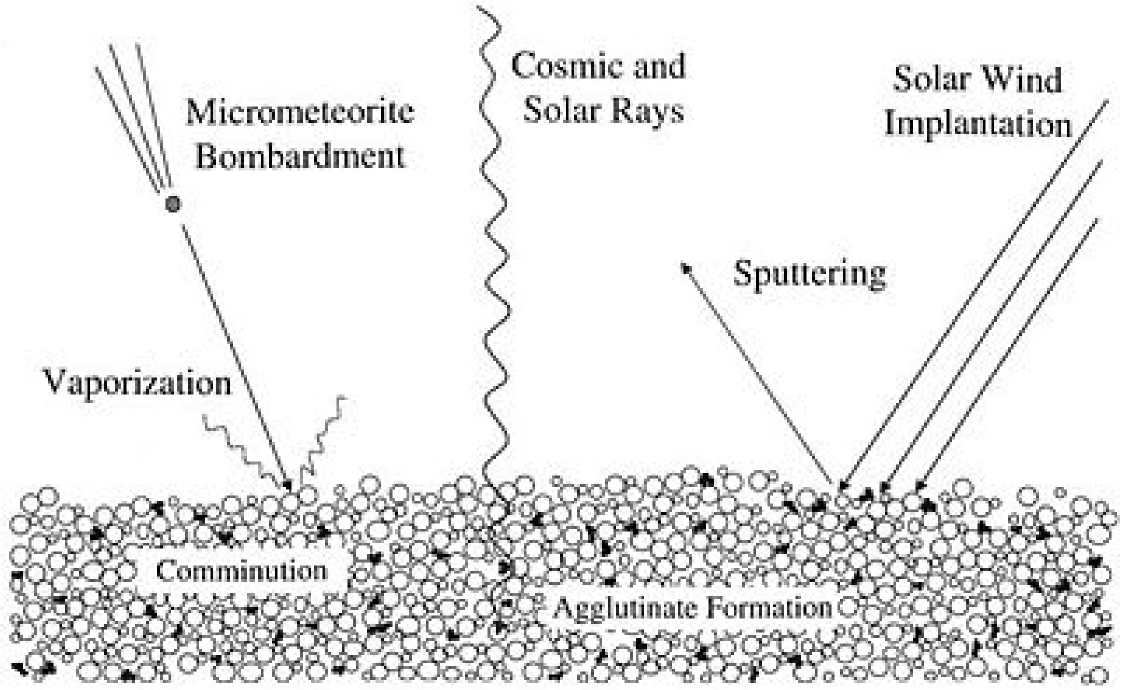

Figure 5.2: A schematic drawing of the different Space Weathering processes, Credits: (newworldencyclopedia, 2015)

differently composed inclusions, or simply trapped atoms such, that they can escape the solid matrix via diffusion. Its effectiveness is thereby influenced by volume diffusion from the interior of grains to their surface, surface diffusion between sites that offer different desorption energies, and the degree of electric excitation or de-excitation. (Killen et al., 2008; Domingue et al., 2014) The thermal desorption rate itself is determined by diffusion, grain size and lifetime on a surface, and the abundancy of lattice defects which facilitate and enhance diffusion. (Killen et al., 2008, 2004; Domingue et al., 2014) Diffusion generally acts more rapidly in smaller grains, which would lead to a quicker depletion in volatiles such as O or H, but due to their larger surface/volume ratio, smaller grains are by far more effective in repository for adsorption. (Killen et al., 2004; Domingue et al., 2014)

Figure 5.2 Shows a schematic drawing of the different Space Weathering processes.

5.2 Influence of space weathering on asteroid classification

Since the first Apollo missions and the samples of lunar regolith they returned to Earth, it has been noted that the spectrum of a weathered piece of soil shows rather

large differences to the spectrum of an un-weathered despite having nearly the same elemental abundancies, and a similar chemical composition. This difference, extends for all air-less surfaces throughout the solar system, making the characterization of asteroid composition nearly impossible, and the linkage of asteroid and meteorite spectra that much harder. The biggest problem for reliable classification of asteroid surfaces however is the major difference between the degrees and direct effects of space weathering on different surface compositions at different locations within the solar system. For example, the development of nanophase iron, that is one of the most prominent agents of spectral effects of space weathering seems to be largely absent on Vesta, leaving the determination of spectral changes for this body to other effects. The various mechanics remain poorly understood, but from lunar samples and various laboratory experiments, which will be further explained in the next sections, have left some conclusions.
Overall it can be said that the continuing influence of space weathering on any surface tends to lower the albedo (most likely due to the presence of nanophase iron, agglutinates, and patinarims, which tend to be by far darker than the minerals they were previously bound in) and leads to a higher reflectivity in the higher wavelength resulting in a general red-slope of the entire spectrum. Additionally, it produces a depth variation that ranges from as low as a few percent up to $20-30\%$. For many minerals, the reflectance slope can vary up to $10-15\%$. (Clark et al., 2015)Physical mechanisms of space weathering with their tendency for preferencial fracturing of surficial minerals further lead to a domination of these materials in the spectrum, as the finer grained regolith does contribute disproportionally more to the overall reflectance, due to the higher surface/volume ratio. The entire magnitude of surface alterations depends on so many different factors that enhance and inhibit each other in so many different ways, that it is sheer impossible to completely characterize the entire process and deriving effects. This leads to an inter-species (within the same taxonomic type) variability of such a magnitude that it can simply not be defined which spectral reflectance characteristics are due to composition, and which are due to different interactions between space weathering mechanisms. The space weathering itself thereby does not really make it hard to distinguish rather big differences in the surficial composition of an asteroid (the large asteroid complexes, differ so much from each other, that the different degrees and effects of space weathering should not have any impact on that), but instead aggravates the finer classification and deduction of exact composition, as would be required for the purpose of asteroid mining. While it does not actually blind us, it just disguises the vital information. This means for the future development of a space economy, that science either has to learn more about the various interactions between the different space weathering mechanisms in respect to the differences in mineralogies of the surfaces, or directly examine the direct effects in situ with further space missions to asteroids to provide the information necessary for the

commercial use of asteroid materials.

5.3 Laboratory results

To cope with the influence of space weathering on the spectral properties of asteroid surfaces, a series of laboratory experiments have been conducted to examine micrometeorite and ion bombardment, and desorption effects on minerals and mineral grains.

To study the influence of micrometeorite bombardment on mineral surfaces, powdered silicates like orthopyroxene, clinopyroxene, and olivine have been acted on with pulsed lasers. (Moroz et al., 1996; Yamada et al., 1999; Sasaki et al., 2001, 2003) The pulsed lasers were to produce vapor deposited nanophase iron, that is often used as a proxy to determine weathering rates, and enable direct comparison between the spectra of the unweathered and weathered powder. There are concerns though, how accurately laser pulses represent micrometeorite bombardment, especially regarding the depth of penetration and the influence of the temperature, as most experiments have been conducted at room temperature. As the effects of laser irradiation depend on the energy flux per single pulse, pulse duration, and the used wavelength. (Chrisey et al., 1994; Domingue et al., 2014) The fluence determines whether the experiments simulate a low impact energy regime, where mainly thermal and chemical effects are being induced, simulating impacts with either small, or low energy micrometeorites, or a high impact regime resulting in vapor production depending on target properties. To properly simulate micrometeorite bombardment, the choice of laser parameters, in respect to the laser absorption properties of the investigated sample is extremely important. For a typical silicate sample, as was used most commonly for these experiments, the laser absorption ranges from strong to medium, thus a fluence of 0.5 and 2 J/cm^2 per pulse was used to induce vaporization. (Baeuerle, 2000; Domingue et al., 2014) Since most effects studied, show a high dependency on the target temperature, the pulse frequency and duration had to be chosen carefully, as a higher frequency and duration tended to heat the sample, influencing the experiments results.

The first pulsed laser experiments were performed on ordinary chondrite material, and used a micro-second pulsed laser to simulate the reddening and darkening effects on reflectance spectra. (Moroz et al., 1996; Domingue et al., 2014) However, a microsecond pulse is by far longer than the micrometeorite impact timescale, leading to extensive melt all over the sample, and therefore the spectral change observed has probably resulted from the formation of glass. (Sasaki et al., 2001) Later pulsed laser experiments have used a shorter nanosecond pulse duration, ensuring that only the target particles would heat enough to vaporize, keeping offsite melt at bay.(Yamada et al., 1999; Hiroi and Sasaki, 2001; Sasaki et al., 2001, 2003) Hiroi and Sasaki (2001) used a nanosecond-pulsed infrared laser at 1064nm wavelength on pressed silicate pellets, that showed progressive darkening and reddening with increasing shot number. This change in the UV to NIR spectrum was interpreted as increasing formation of nanophase iron enriched coatings on the surface grains. It was later noted that some of the spectral change however may have been due to the infrared laser progressively damaging and stressing of the surface properties by thermalization. (Brunetto et al., 2006b; Hiroi and Sasaki, 2001; Domingue et al., 2014) It was proposed that an ultraviolet laser would instead only break surface molecule bounds and ablation via a higher frequency in cooling and heating, and thereby inflict less direct damage to the surface minerals considering their spectral effects. Experiments using an UV laser simulated the energy dose that would be transferred on a surface by micrometeorite impacts over the time-period of 10^8y at 1 AU, producing about 50% higher spectral slopes than Hiroi and Sasaki (2001), indicating that UV lasers were after all a better analogue to micrometeorite bombardment induced space weathering reflectance changes. (Brunetto et al., 2006a,b; Hiroi and Sasaki, 2001; Domingue et al., 2014)

As most space weathering effects strongly depend on surface composition, it was no surprise that many experiments conducted the way previously described, showed large variations in spectral change with differently composed samples. Sasaki et al (2001) compared the spectral change induced by the same laser on samples of low iron olivine with 8.97 $wt\%$ FeO, and pyroxene with 9.88$wt\%$ FeO, finding that spectral changes were stronger in the olivine samples. Similar results were gained by Marchi et al. (2005) when again using low iron olivine and this time orthopyroxene. Again, the larger spectral change was found to be induced on the olivin sample, proving the compositional dependency of both micrometeorite impacts, and physical sputtering.(Sasaki et al., 2001; Marchi et al., 2005; Domingue et al., 2014)

As of now it is not clear whether UV or IR lasers are the better simulant for meteorite impacts. After all it may be that both are relevant to simulate the different conditions at different heliocentric distances in the solar system. IR lasers may for example be better proxies for mercurial space weathering, with presumably high thermal energies and massive melt and vapor production. UV lasers however, tend to better represent micrometeorite impacts on asteroids, which are thought to be far less frequent and with a lower energy, thus resulting a lower overall melt production. (Domingue et al., 2014)

Due to these lower micrometeorite impact energies, and lower flux of interplanetary dust compared to the lunar environment, a number of teams have proposed that irradiative mechanisms dominate space weathering surface alterations. Additionally, an inverse correlation of the degree of reddening of asteroid surface spectra with the solar distance (flux decreases as $1/r^2$) has been observed, which has strengthened the suspicion that radiative weathering processes dominate the overall spectral change amongst asteroids. However, as the mean composition of asteroids also changes with solar distance, and space weathering mechanisms strongly depend on surface compositions these observations have to be treated carefully. (Marchi et al., 2006; Loeffler et al., 2009; Domingue et al., 2014) More convincing evidence for the domination of solar wind irradiation has been found in the asteroid samples from Itokawa, which were returned to Earth by the Hayabusa space probe. Noguchi et al. (2014) showed that nanophase iron contained within sample grains, were surrounded by iron depleted areas, supporting the thesis for in situ production of $npFe^0$ by radiative rather than vaporization mechanisms. This is because when nanophase iron is produced via vaporization, the depletion of Fe in the surface particles does not focus on the area directly surrounding the $npFe^0$ inclusions, but rather at the original impact site of the micrometeorite, thus making the depletion in iron an overall surface effect. (Noguchi et al., 2014; Domingue et al., 2014) Anyway, to better understand spectral changes of the asteroid population a number of experiments simulating radiative space weathering processes have been conducted. For example, material of an ordinary chondrite has been irradiated with 60 keV Ar^{2+} ions over a series of different ion fluences and was studied with bidirectional reflectance measurements from 0.3 to $2.67\mu m$. The result was progressive reddening and darkening of the spectra that was comparable to previous postulations of asteroid weathering rates. (Strazzulla et al., 2005; Domingue et al., 2014) Brunetto and Strazzulla (2005) conducted experiments using a variety of silicate samples like olivine, pyroxene, and serpentine and irradiated them with different ion species including H^+,He^+,Ar^+,and Ar^{2+} at energies between 60 and 400 keV.(Brunetto and Strazzulla, 2005; Domingue et al., 2014) Examining the reflectance properties from 0.25 to 2.7μm and through Raman spectroscopy, they found correlations between the darkening, reddening and decrease in spectral slopes with the formation of nuclear displacements within the sample materials. They concluded that the observed spectral alterations can be contributed to the amorphization of the uppermost layers of the sample. The observed decrase in band areas is thereby due to changes of the surface materials optical properties. (Brunetto and Strazzulla, 2005; Domingue et al., 2014) Later, Loeffler et al. (2009) decided to study the spectral changes in combination with the structural changes inflicted on the surface by irradiating a sample of olivine with 4 keV He^+ions. Their setup produced spectral changes, similar to those of the pulsed laser experiments investigating the micrometeorite impact effects conducted by Brunetto et al. (2007), as well as earlier experiments examining the influence of solar wind irradiation by Strazzula et al. (2005) and Brunetto et al. (2006). (Strazzulla et al., 2005; Loeffler et al., 2009; Brunetto et al., 2006b; Domingue et al., 2014) It was clearly demonstrated that the reddening of the spectra was caused by an increasing enrichment in nanophase iron within the sample, which was detected using X-ray photoelectron spectroscopy. (Loeffler et al., 2009; Domingue et al., 2014) Due to spectral changes only being observable at higher fluences, Loeffler et al. (2009) concluded that not amorphization, but chemical reduction was responsible for the measured alterations in the absorption spectra. The only spectrum changes observed however, were decreases in band areas, and reddening but no darkening, which was explained by the small size of the formed nanophase iron that was measured. Noble et al. (2007) have showed earlier, that smaller $npFe^0$ tend to contribute relatively more to reddening and less to darkening of a spectrum than larger sized deposits.(Noble et al., 2007; Domingue et al., 2014) Both spectral changes that did occur were more pronounced in the lower wavelengths. The reddening observed in the olivine sample occurred predominantly below 1.07μm, and the decreases in band areas were larger at the band I (1μm) absorption feature, than at the band II (2μm) absorption feature, both of these bands are used to determine the Fe content of olivine and pyroxene, and thus vital to the understanding of spectral behavior of space weathering mechanisms. This focusing of space weathering induced effects on lower wavelengths has also been observed in lunar and asteroidal spectra. Another important aspect that was examined by Loeffler et al. (2009) was the variation in the production of nanophase iron, and thereby the induced spectral changes between powder and slabs of these minerals. They found that the formation of $npFe^0$ was about two times more rapid of the flat surfaces than on the powder of the same sample. This was explained with the greater redeposition rate in powders compared to solid and un-comminuted surfaces. It has long been noted from several experiments that, when sputtered material is being redeposited, it is at least partially oxidized. (Mauvernay et al., 2007; Loeffler et al., 2009; Domingue et al., 2014) Whilst the production of nanophase iron by irradiation does itself not require redeposition, it has been observed that some two thirds of the material ejected during irradiation is being redeposited. This value fits well with the postulated 70% redeposition rate that was postulated by Cassidy and Johnson (2005). This leads to the conclusion that all factors that enhance redeposition such as the abundance of a fine-grained regolith, or greater surface acceleration, simultaneously inhibit the production of $npFe^0$. (Cassidy and Johnson, 2005; Domingue et al., 2014) To find the dominant weathering processes for different celestial bodies, a direct comparison between the weathering rates of solar irradiation, and micrometeorite impact driven processes is necessary. Loeffler et al. (2009) proposed a characteristic time for radiative space weathering of some 5000y based on their experimental experiments, but this time frame does not include interactions between the effects of both ion and micrometeorite bombardment. Gardening for example, with its tendency to overturning the surface and permanently expose fresh un-weathered soil to solar radiation

and thereby keeping the surficial mean age lower, increases this time frame signifficantly. It was estimated that the reddening effect of radiation induced space weathering should saturate some two orders of magnitude more rapid than that of micrometeorite impact driven vaporization and melt production. (Loeffler et al., 2009; Domingue et al., 2014) The analysis of solar wind irradiation conducted by Strazzula et al. (2005) showed a more realistic time frame of about $10^4 - 10^6$y for the observed spectral change, which is consistent with the results of Brunetto and Strazzula (2005), estimating a timescale of 10^6y for irradiation induced space weathering spectral effects.(Strazzulla et al., 2005; Brunetto and Strazzulla, 2005; Domingue et al., 2014)
Most experiments regarding Desorption induced by electronic transitions focused on either PSD or ESD individually, despite them having quite a bit in common. It has been showed that both ESD and PSD have threshold energies of some 4 eV and the atoms desorbed by them have suprathermal velocities. PSD desorbed sodium for example has a peak speed of some 900 m/s. (Yakshinskiy and Madey, 2000; Domingue et al., 2014) Experiments studying ESD have been mainly conducted on samples of Lunar basalt covered in a Na monolayer, SiO_2, as well as on Na- and K-bearing glasses. (Yakshinskiy and Madey, 2000, 2003, 2004, 2005; McLain et al., 2011; Domingue et al., 2014) They did provide evidence for a dependency of the desorption yields on temperature, meaning that different surface temperatures on asteroids will considerably influence the removal rate of atoms and molecules from their surfaces. The desorption rate of Na for example was observed to increase tenfold in the temperature range of 100-470K, which can be considered a temperature range on which most asteroids lie. (Yakshinskiy and Madey, 2004; Domingue et al., 2014) These changes in the desorption yields have been ascribed to thermally induced alterations in grain to surface bonding sites. They are explained by changes in density and the locations of atomic or molecular defects in atomic lattices, at which different temperatures induce alterations in the position within the crystalline atomic structure relative to nearby atoms, which enhance the effectivity of ESD processes. (McLain et al., 2011; Domingue et al., 2014) This explanation is consistent with the expansion of atomic lattice, increased hole localization at molecular defects, and the diffusion of volatiles outwards the grains on surfaces. (Chen et al., 2005; Domingue et al., 2014) A further important statement, that derived from these examples, is that there is a significant difference in desorption yields from surface covering films and regolith, due to atoms desorbed from fields escaping with a far higher efficiency than those from regolith. This is because of the sticking probability of desorbed atoms within a porous medium made up of fine grains. Measurements conducted by Yakshinskiy and Madey (2005) on Na and K showed that the sticking probability of Na decreased with an increase in temperature, whereas K has a constant sticking probability between 100 and 500K. Therefore, the yields of electronic transition induced desorption is extremely

species dependant.(Yakshinskiy and Madey, 2005; Domingue et al., 2014)

Studies of thermal desorption have been conducted on samples of SiO_2 and Al_2O_3 which were coated in layers of sodium, showing that desorption yields thereby are related to the temperature involved, as was expected, and the thickness of the sodium coat on the samples. (Madey et al., 1998; Shao and Paul, 1993; Domingue et al., 2014) Fractional sodium coatings around SiO_2 thereby desorb mostly beyond 500 to 600K, whereas multi-layer desorption peaks at 350K and therefore dominates in the lower temperature segment. On Al_2O_3, both fractional and multi-layer sodium have a typical desorption temperature of about 300-400K.(Madey et al., 1998; Shao and Paul, 1993; Domingue et al., 2014; Killen and Ip, 1999) The rates of thermal desorption from metal-oxides therefore depends largely at the specific composition and the presence of other elements in low concentration. (Killen et al., 2008; Domingue et al., 2014) The thermal desorption energy of K in the same type of mineral can increase from 0.83 to 2.35 eV if only $2wt\%$ Mn are included. (Kotarba et al., 2004; Domingue et al., 2014)
Despite, so far not bringing science any closer to characterize the direct influence space weathering has under the various conditions asteroids suffer in space on the spectral surface properties, these experiments have given an insight in how these processes work. Too many co-dependencies have been detected already as to hope for the ability of extrapolating the spectral alterations and deduce the 'unweathered' spectrum from Earth made observations. If anything, they made it abundantly clear that space probe missions will have to be launched at a great scale if any progress towards the realization of asteroid mining is to be made. Clark et al. (2015) therefore proposed to map the surface manifestations of space weathering on the asteroid 101955 Bennu, once the data collected by OSIRIS-Rex is retrieved. (Clark et al., 2015) Their space weathering map will thereby an expression of the probability that each surface facet exhibits space weathering. To each surface facet, rankings in continuum slope, band depth, albedo, crater proximity, boulder proximity, slope of location, local particle size, and proximity to regolith regions will be assigned. These rankings are supposed to place each single facet on a scale expressing the likelihood according to each of the metrics listed above. The algorithm for each of the metrics is a relative ranking of every single facet, according to the range of values exhibited in the data set for each metric. If a facet for example exhibits an albedo, which is extremely different to the mean albedo of the entire surface, then it is extremely likely that it has undergone severe spectral alteration by space weathering. The same counts for every other aspect observed, like continuum slope et cetera. It is important though that every other plausible explanation for an observed difference needs to be taken into account when estimating the probability of each indicator being associated with the effect of space weathering. The optimal approach for this would be to

identify a patch of freshly exposed surface material to verify the assumption of mineralogical composition. (Clark et al., 2015) This would give further insight in the overall effects on spectral classification of asteroidal surfaces.

Chapter 6

He3

6.1 Formation of He3

Most of what we know today about the formation and enrichment of He3 is deduced from our lunar observations and missions. He3 itself is an extremely scarce and volatile isotope of Helium, and has often been proposed, to become our most important fuel in the future, due to its properties that make it comparably easy to use for controlled fusion within reactors. Helium is such a light element, that most planets cannot keep it within their atmosphere for too long, as it easily escapes. Only large gas giants such as Jupiter are thought to contain large amounts of He3. Early Moon-missions however, have made the discovery that there are comparably large enrichments of He3 in some lunar soils. (Heiken et al., 1991) As He3 has often been proposed to be one of several materials that could be gathered by asteroid mining operations, an assessment of potential He3 content of asteroids should be done. Therefore, at first, the source of He3 content within lunar soils needs to be identified. As the moon has an even lower gravitation than Earth, the concentration of He3 in lunar soil must be caused by external influences and can't have been caused by the moon's initial content of He3. Therefore, all of the lunar soil's He3 content must have been brought there by external factors, or formed in situ. The only way He3 could have been brought to the moon stored within material is through impacts of meteorites which have had a larger content of He3 respectively. However, as He3 is extremely volatile, melting of a material can release it, as is shown by the absence of any noteworthy He3-concentration within materials that have undergone melting processes on the moon (Heiken et al., 1991). Ozima and Podosek (1983) have already deemed this fraction of noble gas enrichment to be negligible.(Heiken et al., 1991; Ozima and Podosek, 2002) The extreme heating by friction a meteorite suffers during impact would have therefore most likely released the He3 once it reached the surface. The only way lunar soil could have enriched in He3, is therefore by in situ formation, or solar-wind-induced ion-implantation. Helium is the second most abundant component of solar wind, with an isotopic ratio of He3/He4 of $4 * 10^{-4}$, which is substantially higher than the terrestrial value of $1.4 * 10^{-6}$. (Heiken et al., 1991) This seems to be the dominant source of He3 within lunar regolith, however, additionally some could have been formed as a spallation product of reactions between lunar surface and highly energetic solar and galactic cosmic irradiation. (Heiken et al., 1991) This assumption seems to be supported by the fact that there are correlations between isotopic ratios of the solar wind components, and noble gas concentrations within lunar soils, with any small differences being easily explained by different release rates for different isotopes. (Heiken et al., 1991) It therefore can be assumed that the contribution of the solar-wind must be the dominant factor in noble gas (including He3) enrichment. As implantation of ions, and spallation reactions only occur in the upmost atomic layers of the surface, He3-enrichment can be considered a side effect of space-weathering, making it rather interesting for asteroid miners. Since He3 content within soils is a direct result of space weathering processes (spallation and ion implantation), we know its area of effect, which ranges only around the topmost few nanometers of the surface, scaling more with surface, than volume of enriched grains, with a saturation level of implanted ions being easily reached within a few tens of years (Heiken et al., 1991; Warhaut et al., 1979). However, Apollo deep drill core samples have shown bulk densities of He3 within up to 3 meters in depth that do not vary that much with that of the surface. (Heiken et al., 1991; Pepin et al., 1975) This means that sufficient gardening by micrometeorite bombardment must be present to bury particles enriched with He3. This is supported by the fact that grains of different saturations have been found well mixed in every layer, meaning that some of them have spent more time being exposed to the surficial solar wind than others before being buried by impact ejecta. (Heiken et al., 1991)

6.2 Estimation of He3 in asteroid regolith

To properly estimate any potential He3 content within asteroid regolith we therefore need to compare the environments of the moon to those of target asteroids. For that it is necessary to specify which asteroids are most likely to keep the He3 enriched regolith on their surface: NEOs or Main Belt asteroids. Binzel et al. (2010) proposed close encounters with Earth, and other major planets as source for fresh, unweathered material at an asteroids surface, since the gravitational influence of such a close encounter in combination with the comparably low gravitation of NEOs themselves, are able to sweep an asteroids surface clear of a large fraction of its original small particle surface population. (Binzel et al., 2010) As these are exactly the small, and loose particles which contain the largest fraction of He3, this necessarily leads to the conclusion that most NEOs can't have a feasible concentration of He3 within their surficial layers. Therefore, this estimation concentrates on Main Belt asteroids, where surface cleansing close encounters with planets do not happen.

Therefore, I propose to at first, revise the solar wind mechanics. The further away from the sun, the weaker is the intensity of the solar wind. While cosmic rays do have an impact at He3 generation, their contribution is still negligible as stated beforehand. Therefore, the effectivity of He3 enrichment is directly proportional to the density of the solar wind at a specific area. Assuming an asteroid somewhere near 2 AU, at the innermost extension of the Main belt, the density of solar wind particles should be roughly half of that at the 1 AU average solar distance of the Moon. Still, at the moon the maximum saturation is reached within a relatively short time (very few decades)(Heiken et al., 1991) therefore, I assume that within such small differences, even if it takes twice as long, should still be comparably low to the time it takes for the average surface particles to be buried by micrometeorite impacts. This is a relatively rough assumption, as much about the micrometeorite flux within the main belt is still poorly known, therefore a more precise estimation needs to wait until exact parameters are being modelled and investigated. For this estimation of the He3 content of asteroid regolith, I assume the enrichment of He3 to be relatively independent of the exact intensity of solar wind, as a full saturation should at least on average still be plausible.

Comparing the micrometeorite environment of Moon and the Main Belt, is for the same reason as above no easy task. Since velocity and size distribution of micrometeorites at the Main Belt area are currently not available, they have to be substituted and estimated. However, a wide set of mass and velocity of micrometeorites will be tested to generate a wide spectrum of possible outcomes, which will be discussed later. Zook (1975) reported of average meteorite impact speeds at the moon ranging between 13 and 18 km/sec, with velocities rising with decreasing size of impacting particles. (Zook, 1975) Hoffmann et al. (1975) give an average speed of 8km/sec for particles in the mass range of $10^{-8}g - 10^{-11}g$, which corresponds to sizes between roughly 10-100 μm if using a density of around $2.7g/cm^3$. Such a density range seems reasonable for this estimation, as according to Grun et al. (1984) this is the typical value in which most of the meteorite population resides. (Grün et al., 1985) Borin et al. (2009) used the values and estimations presented in the former paper, and reached the conclusion that between 10 and 100 μm particle sizes no significant change in velocities can be observed. (Borin et al., 2009) While they recognized this only for the mercurial micrometeorite flux, they stated that the major source of differences would be the pressure of the solar wind which only starts to work efficiently on smaller particles. In the Main Belt area, the pressure would be lower still, meaning that only by far smaller particles than 10 μm would be strongly influenced by it. This size range however is not used for this estimation, thus we assume an equally simple velocity distribution between sizes. As this is the typical particle size of micrometeorites reviewed in scientific literature, these are the size ranges in which this estimation will operate. Since there is a lack of data about the micrometeorite environment in the main belt, the conditions for our target asteroid will have to be estimated based on the nearest data available, in this case Mars. Since only a small fraction of Marsian micrometeorite environment is expected to come from its natural satellites, (Pabari and Bhalodi, 2017) this seems a good overall representation of micrometeorite environment at around 1.6 AU. As the Marsian micrometeorite environment is similar to that of Earth, we assume a similar average in the Main Belt. As these assumptions may be wrong, both higher and lower average values for mass and velocity of micrometeorites will be calculated to propose a maximum boundary for He3 content on Asteroids in different environments. This seems necessary, as for example Borin et al. (2009) assume the average velocity of micrometeorites to drop of with larger distance from the sun, which would lead to lower impact speeds in the Main Belt. (Borin et al., 2009) Gruen et al. (1985) on the other hand suggest higher impact speeds in meteorite/meteorite collisions than on Earth or Moon, due to their larger eccentricity and inclination, which is also true for many Main Belt asteroids, suggesting relatively higher impact speeds there than on Earth. (Grün et al., 1985)

To find a good maximum boundary for He3 content of Main Belt asteroids both higher and lower values for velocity will have to be taken into account until sufficient data is available. Since all He3 is only deposited within the upmost few nanometers, finding out which fraction of the topmost layered particles returns to the body's surface after micrometeorite impact is critical. Therefore, the particles take-off velocity after impact is vital. If the particles velocity surpasses the escape velocity, said particles with all their He3 content will be lost to space. To create a upper boundary for He3 content on asteroids, we need to compare the velocity distribution of the topmost particles after impact with that of the moon in respect to the respective escape velocities at hand. The Moon's escape velocity amounts to 2,370 m/s, while that of an asteroid with only 1000m in diameter and a density of $3g/cm^3$ is only around 0.65 m/sec.

The velocity distribution of particles after impact is given by:

$$\nu = C_1 H^{\frac{-1}{\mu}} \frac{x}{R}^{\frac{-1}{\mu}} (1 - \frac{x}{Rn_2})^p$$

$$R = HaU^{\mu}\frac{\delta}{\rho}^{\nu}$$

$$H = 1.61 H_2 \frac{\rho}{Y}^{\frac{\mu}{2}}$$

(Housen and Holsapple, 2012)

μ	0.55
C_1	1.5
H_2	1.1
n_2	1
p	0.5
$\rho(kg/m^3$	3000
$\delta(kg/m^3$	2700
Y (MPa)	30

Table 6.1: Literature values for the variables, Credit: (Housen and Holsapple, 2011)

H is a constant in dimensional form for a given target material and can be either directly measured during impact experiments or calculated as in this case by using Y, the material strength and its respective constant H_2 to get realistic results for H. ρ is as usually the density of the target material and σ the density of the impacting material. $U(m/s)$ is the impactors speed, and a (m) its radius. R is the crater radius, depending on impactor size, speed, and density, as well as on the material strength and density of the target material. C_1,n_2,and p are constants determined from fits to ejecta data, and ν and μ are the exponents in the point source measure of the impactor. x/R is used to get the velocity distribution by a dimensionless radius with x being the distance to the impact site. (Housen and Holsapple, 2012) For this estimation we assume for simplicity a spherical rock asteroid with a surface similar to the average surface of the Moon, and a diameter of 1000m. The data used hereby, is taken from housen and Holsapple (2011).

After I used the formula above to calculate the crater radius, the crater has turned out to be extremely large in comparison to the only few nanometers of the He3 enrichment zone, the He3 bearing particle area can be treated as 2-dimensional. With a known escape velocity and the particle velocity decaying by distance to the impact site we get a minimum distance to the site within which any He3 is lost either to ejection, or by release, as any particle directly at the impact site is either molten or vaporized releasing its He3 content in the process as explained earlier. Therefore, we can estimate how much of the He3 bearing particles return to the surface being buried over time enriching the subsurface in He3.

According to the results I calculated for the velocity distribution, the percentile He3 loss will rather much stay the same for different sizes and velocities of impacting micrometeorites. The only thing that does change by varying the sizes and impact velocities is the crater radius and thereby its overall effectiveness in resurfacing the

Impactor diameter	Impactor velocity	Crater radius	Radius at which the particle surpasses the escape velocity on the asteroid	Radius at which the particle surpasses the escape velocity on the Moon
10μm	8000m/s	94.53μm	94.51μm	11.31μm
50μm	8000m/s	472.67μm	472.57μm	56.53μm
100μm	8000m/s	945.33m	945.14μm	112.06μm
10μm	4000m/s	64.56μm	64.54μm	7.72μm
50μm	4000m/s	322.84μm	322.74μm	38.61μm
100μm	4000m/s	645.68μm	645.55μm	77.22μm

Table 6.2: Results in mass-loss for different sizes and velocities of impacting particles on the Moon and on an asteroid

body. The moon looses about 14.3% of the He3 bearing particles ejected from the crater during impact each time, whereas the asteroid looses 99.98%. This would only change for impact velocities so low that they are themselves comparable to the escape velocity, which is rather much impossible, or if other materials than rock are chosen. For other materials than rock however, it is extremely hard to make any guesses to possible He3 content, as the lunar regolith is so far the only one known to contain He3 in relatively large concentrations, therefore no data is available for different types of soil.

6.3 Discussion

Due to the extremely low gravitation on asteroids, and the relatively high material strength, these simulations were done according to the laws for strength dominated impacts. These two extreme values further diminished any real chance of finding large concentrations of He3 within asteroid regolith, as the moon contains most of its fraction, whereas an asteroid of a diameter of 1km and $3g/cm^3$ density can keep almost none on its surface during micrometeorite impacts. The chosen particle sizes and velocities are a relatively good estimation as they seem co contain a reasonable range of values within them and their results show not that much of a difference between one another. Due to this, and the fact that the results seem to be rather extreme in showing that an asteroid can not contain any deposits of He3 bearing regolith worthy of exploitation, it is rather safe to assume that even if the velocity distribution of micrometeorites within the main belt differs more than expected from that at 1 AU, there is still no hope to find He3 stored within an asteroid subsurface. Unfortunately, this strongly contradicts previous hopes to use He3 from asteroid regolith as a power source for self-sustaining asteroid mining machinery and as a clean energy source for Earth eventually.

Chapter 7

Asteroid Mining

As mankind advances scientifically and technologically, the view on asteroid mining changes from pure science fiction to actual science. Since the late 80's and 90's more and more scientists recognize the commercial and scientific use of space resources as feasible within the next decades. Many have proposed different approaches, but also problems, which have to be solved before mankind can lavishly spend all the wealth surrounding us in the solar system. The possibilities are endless, but so are the obstacles laying before us, that we have to overcome. These problems begin with the uncertainty in the estimations of material quantity at hand, which asteroids we should choose for our explorations, and end at the monumental task to actually conduct a form of mining that has but a few technical similarities with terrestrial mining, the only kind of mineral gathering we have done so far.

7.1 Abundant materials

Asteroids have a very diverse composition and, thus the use of a certain objects will always depend largely on the particular characteristics at hand. In Outer space, nearly all resources can be used one way or another. Metals, especially the rare ones could achieve high prices on terrestrial markets, whereas volatiles could be used to further mankind's expansion in outer space. Relatively worthless regolith even could be used as radiation shielding and help to sustain human life in the harsh conditions of space environment. In this section an overview of the resources available on asteroids is given.
In order to understand which materials can be expected to be found on the various asteroid types, it has to be understood which processes determine the compositional characteristics of these smallest celestial bodies. The materials and minerals found in different asteroid types depend on their formation history and their evolution. When an asteroid differentiates the heavier elements and molecules tend to concentrate on the inner regions, whereas the lighter ones form the mantle and crust region. Thus, when the planetessimal is later broken up, (presumably usually along the borders of materials with different strength) asteroids with extremely different compositions are the result. But undifferentiated celestial bodies, too

show extreme variations amongst their chemical compositions, which is attributed to their formation location, and time. The solar nebula from which asteroids form is assumed to be rather homogeneous in elemental distribution and abundancy, yet different condensation temperatures and environmental conditions influence the composition of the bodies to be formed as much, as the later possible differentiation and fracturing. (Trigo-Rodríguez et al., 2017) These observed chemical fractionations of elements among chondritic meteorites, are best understood as the result of a quenched equilibrium between phases of nebula of solar compositions. (Palme, 2001; Trigo-Rodríguez et al., 2017) The equilibrium model assumes a cooling, initially hot solar nebula. As the sun was the only major source of thermal energy, the local temperature of the cooling nebula areas depended largely on heliocentric distance. At a given region, elements in the gas phase, with a condensation temperature higher than the local temperature, were incorporated into the forming planetesimals. Chondritic meteorites also show abundancies of volatile depleted species in front of materials with higher condensation temperatures, which is attributed to the constant loss of mass from the disk, where the gas was being removed. This model is believed to be consistent with the uniform isotopic composition of chondritic materials with the only exception of oxygen. (Palme, 2001; Trigo-Rodríguez et al., 2017)
Therefore, elements are classified based on their relative volatility, the temperature at which 50% of the respective elements have condensed, in the solar nebula condensation period. This is the primary parameter determining the chemical composition of chondrites. (Wasson, 1985; Palme and Jones, 2003; Trigo-Rodríguez et al., 2017)
In a cooling nebula, with a density of about 10^{-3} atmospheres refractory elements start to condense at a temperature between 1450-1800 K as calcium, aluminum and titanium-rich oxides and silicates along with refractory trace elements like barium, beryllium, vanadium, thorium, uranium, platin group- and rare earth-elements. At lower temperature ranges between 1350 and 1450 K, major elements condense as magnesium-silicates (like fosterite and enstatite) and iron condenses alongside with nickel, and cobalt to form metallic molecules. Alkalis and moderately volatile siderophiles condense between 650 and 1250 K. Below 650 K iron starts to react with sulfur forming troilite, and even highly volatile elements such as the halogens and inert gases condense. (Lodders, 2003; Wai and Wasson, 1977; Trigo-Rodríguez et al., 2017)
Thereby it makes sense to divide elements into sub-categories based on what they tend to form, like siderophiles condensing as metals, lithophiles condensing as oxides, and calcophiles condensing as sulphurs or some other calcogen other than oxygen. Complete lists of 50% condensation temperatures for the various elements and groups have been provided, with the exception of hydrogen and helium. However, these lists are generally not too reliable for trace elements compared to major elements, since they condense in solid solution with major phases, making thermo-

dynamic properties rather poorly constrained. (Lodders, 2003; Wai and Wasson, 1977; Trigo-Rodríguez et al., 2017)

Whereas these estimations are good indicators for materials to be found respective to asteroid classes, arguing for chondrites being rich in volatiles and certain trace elements, and the bulk of relevant metals to be found embedded within less primitive bodies. The estimations on the amount and abundancy of these valuable materials is however only based on statistical estimates derived from spectroscopic surveys and laboratory analysis of recovered meteorites. Therefore, one always has to keep in mind the difference between astronomic and commercial accuracy. As explained in the previous sections, the various effects of space weathering make any spectroscopic based estimations speculative, and meteorites undergo severe alterations in Earth's environment and the linkage between meteorites and asteroids are largely disputable at best. Still meteorites represent the only accurate account of the materials available on asteroids so far. (Lewis, 1974)

7.1.1 Water

Water is ubiquitous in its existence, and vital for life as we know it. It has an extremely strong bond, and therefore survives harsh conditions. On Earth we have an estimate of 1.4 billion m^3 of water, covering nearly 71% of Earth's surface and despite only some 3.5% being drinking water, and most of it frozen at the pole caps, it is enough to sustain the population. In respect for all the people suffering water shortage and dehydration, it cannot be said that water is worthless on Earth, but the relatively low amounts of water that could be recovered from asteroids in addition to the estimated cost of recovering would hardly justify to mine water and bring it back to Earth. However, in outer space the value of water rockets high, as it currently has to be launched from Earth to outer space. Taking for example the newly designed device Dragon from SpaceX, with a payload of 6000kg, and a complete cost of 140 million dollar, 70 million dollar if the space capsule can be re-used. The price of one liter of water in outer space amounts to a total of 31,400 dollar which could be brought down to some 15,700 dollar when the Dragon is re-used. (SpaceX, 2017)
As meteorites suffer serious alterations during their flight through Earth's atmosphere and once landed, weathering and other chemical interactions with the terrestrial environment, it is hard to determine the water content of asteroids by meteorite analysis. Firstly, most of the water content of the meteorite evaporates to the extreme thermal conditions, and secondly the landed meteorites are highly contaminated with terrestrial water. Thus, to estimate how much water can be found on different taxonomic asteroid classes we need to rely on the spectral properties of their surface. The 3.1micron hydration feature is one of the most valuable

diagnostics. (Elvis, 2013; Nelson et al., 1993; Vilas, 1994)

Observationally the 3.1micron feature poses some challenges though, as it lies at the short end of the L-band wavelength. The width of the L-band (3.2-3.8microns) is set by atmospheric transmissions, and its background is strongly dominated by the black body emission of both, Earth's atmosphere, and the telescope at 300K. Therefore, it will most likely be feasible for only the brightest of NEOs. (Elvis, 2013) Alternatively, the 0.7micron feature can be used, as it lies well within the optical band. (Elvis, 2013; Vilas, 1994) Both, of these two diagnostics correlate well within the C-complex asteroid class, indicating strong hydration of their surface mineralogy, however within the X-complex only the 3.1micron feature has been found frequently, whereas the 0.7micron feature is rare amongst this complex. Therefore, it is believed that the 0.7micron feature suffices to indicate hydration, yet its presence is not required to provide evidence for the abundancy of water. Unfortunately, only few NEOs show this diagnostic, as it is more dominating amongst main belt asteroids, and therefore most likely not of great use for the earliest of asteroid mining projects. (Elvis, 2013; Howell et al., 2011)
One of the most profitable sources of water derived from asteroids would most likely be the hydrated C-class. It makes up about 10% of the entire population of asteroids in the solar system, and contains a water threshold of about $8wt\%$ with an average population density of 1300kg/m^3. (Bus and Binzel, 2002; Chesley et al., 2003; Ross, 2001; Elvis, 2013) This means that a single average hydrated C-class asteroid of about 100m in diameter contains about $54 * 10^6$l of water. Higher abundancies of water up to $20wt\%$ are however believed to be possible within hydrated C-class asteroids and even up to $50wt\%$ if Near Earth Comets were exploited. (Lewis and Hutson, 1993; Elvis, 2013) Of course not only hydrated C-complexes contain water within hydrated minerals, but taking the estimated average S-type asteroids water content of about $0.15wt\%$, it seems to be clear that not every asteroid is a profitable target due to its hydration. (Elvis, 2013) As the name suggests, most water is bound within hydrated minerals which would have to be processed first before being of any use, as will be reviewed in greater detail later.

7.1.2 Iron and Nickel

Iron and Nickel are two of the most important metals for our economy. Whereas iron makes up to 32.1% of Earth's mass, most of it sank to the core during the magma ocean phase and therefore, lies unreachable in the middle of our planet. This left the crust rather depleted in iron where it accounts only for about 5.5% of mass. With an overall mass contribution of about 1.8%, nickel as a siderophile (iron-loving material) bound with iron very early on and is thus also mostly deposited within Earth's inner regions. (Morgan and Anders, 1980; Brown and Mussett, 1981; Elvis, 2013) Therefore, while theoretically being extremely abundant on Earth, these two elements are sooner or later being entirely depleted from the crust with terrestrial mining progressing and the demand for them increasing steadily. As was explained earlier, asteroids either never heated to the point of differentiation, leaving most of their iron and nickel content easily exploitable in a homogenous distribution across the entire body, or have partly to fully differentiated creating vast stocks with enormously high iron and nickel abundancy, which were later fractured and now orbit the sun as metal mountains. It is worth to mention, that especially for nickel, sites of major asteroid impacts, now pose some of the most lucrative mines such as the Sudbury basin in Canada. This formation was created by the impact of a 10km diameter asteroid almost 2 billion years ago and shows how commercially viable asteroids may be once they can be exploited. (Davis, 2008; Elvis, 2013)

On Earth's crust the largest iron deposits are banded iron formations (BIFs) which were created during the great oxidation event between 1.9 and 3.7 billion years ago. (Lyons and Reinhard, 2009; Cloud, 1973) On early Earth most iron was metallic, which was solved in the acidic water of the oceans. However, as life emerged in the oceans in form of bacteria and archaea, both the direct reduction of iron and the production of oxygen by photosynthesis set in, with the oxygen binding the metallic iron forming iron oxides which then were precipitated to the ocean floors. Over millions of years thick layers of various iron oxides formed on the sea floors. Some areas of these so called banded iron formations, a name characterizing the different colors of layers, where later transported via plate tectonics to form continental plates, whereas others were subdued to the upper mantle where they were molten. Some of the largest banded iron formations now lie at the structurally oldest areas of the entire world like in Australia and South Afrika. (Lyons and Reinhard, 2009; Cloud, 1973)

These deposits of iron oxides however require refinery to become high quality steel. Asteroidal iron has never undergone such a massive reduction or oxidation, and therefore is believed to be of much higher quality than terrestrial iron. As a matter of fact, meteorite analysis indicates that a majority of the asteroids bear their metals in free-state, with the only exception of the parent bodies of carboniferous meteorites. (Sommariva, 2015)

Since, as mentioned before, iron does not really have any spectral characteristics, and instead relatively shallows the features of the other minerals present, the only real evidence for asteroidal iron and nickel content derives from the laboratory analysis of meteorites, which have been conducted at great quantities. The largest fraction of iron and nickel can be found in M-type asteroids, the parent bodies of iron meteorites, which make up some 5% of the asteroid population in the inner solar system. (Bus and Binzel, 2002) M-type asteroids are usually composed of around 88% metals, with the best ranging between 82-94% iron and 5.4-18% nickel.

(Ross, 2001; Buchwald, 1975; Elvis, 2013) With a mean density of 5300kg/m^3 that would make some $2 * 10^6$ t of industrial metal stored within a single 100m sized M-type. (Chesley et al., 2003; Elvis, 2013) With the worldwide iron ore production amounting to 2,280 million metric tons in 2015, this would be a market share of ~0.1%. (USGS, 2017) Despite M-type asteroids being the potentially best source for iron and nickel, they can be found in nearly all non-primitive meteorites in significant quantities. Even the ordinary chondrite group that is part of the stony meteorites, which generally have low metal and iron content, can be composed of some 20-30% iron, in special cases even ranging up to 60%. (Sommariva, 2015) Ordinary chondrites are, as explained earlier strongly linked to the S-type asteroids, which make up one of the largest fraction of NEA's with a share of about 40% of its entire population. (Sanchez and McInnes, 2013) Therefore, iron is one of the most abundant valuable resources that could be mined on asteroids, with nickel as a siderophile usually accompanying it. Additionally, the fact that a considerable quantity of the iron at hand is metallic, which means that it is magnetic, which could make the collection of the materials on the asteroidal surface, both easier or harder depending on the extraction technique chosen for the respective surficial conditions.

However, with the current price for iron ore being some 60 dollar/kg, (Infomine, 2017) and 10.5 dollar/kg for nickel (Infomine, 2017), launching a mining operation solely to retrieve the two metals would hardly be profitable. This could change once we have the technical feasibility to use industrial materials directly in outer space for the development of an entire space-born industry. In that case, a demand for these materials in outer space would be created, making them highly expansive in Earth orbit, just the way it currently works with water. For the time being, the mining of asteroid iron and nickel would either have to be stored in the orbit around Earth, or sent down to its surface where a lower price can be achieved right now.

7.1.3 Platin group elements (PGEs)

Platinum group elements (PGEs) consist of 6 noble metals which are grouped together at the periodic table, and include some of the most valuable metals on Earth. They are divided in light PGEs, consisting of ruthenium, rhodium, and palladium; and heavy PGEs including osmium, iridium, and platinum. With their ever-growing prices and scarce availability on Earth, they are truly what most asteroid miners are after.

They are widely used in catalytic processes, like in exhaust filters, electronics, like in circuit boards, or fine jewelry, which they are well suited for due to their high resistance to wear, tarnish and chemical attack, as well as excellent high

Element	Ruthenium	Rhodium	Palladium	Osmium	Iridium	Platinum
Price \$/kg	2,751	43,735	33,083	14,108	34,212	32,856

Table 7.1: Prices of PGEs, Credit: (Infomine, 2017)

temperature characteristics and stable electric properties. (Hunt and Lever 1969) Thus, the demand for PGEs has increased on average by about 5.5% every year within the last 60 years. (Sommariva, 2015) This gives them an actual industrial value, opposite to gold, which will guarantee some stability to longer term price evolution, as far as such a thing can exist at ever fluctuating stock markets.
On Earth they tend to occur together, within the same mineral deposits, generally ultramafic and mafic igneous rocks, which host practically all primary PGE ore of the world. (Harris and Cabri, 1991) Especially the bushveld complex poses one of the largest deposits of PGE-rich minerals, making South Africa one of the largest producer of platinum, palladium, ruthenium and rhodium worldwide. (Xiao and Laplante, 2004) Their overall abundancy is extremely low in Earth's crust with only a few parts per billion, making them some of the scarcest materials on Earth. Only 0.6 palladium atoms exist within one billion atoms on Earth's surface, with similar values for rhodium, platinum, osmium, and iridium. Only Ruthenium is a bit more common with about 1 part per billion, in combination with lower utility promptly resulting in a lower price, as can be seen in the table above. (Sommariva, 2015) The 2007 U.S. Geological survey estimated PGEs contained within mineral concentrations high enough that they can be exploited economically viable to a total of no more than 100,000 tons worldwide. In asteroids they cannot be detected due to the extremely low overall abundancy, and therefore can only indirectly be measured by laboratory analysis of different meteoritic types. They show the highest abundancy in some iron meteorites. The best iron meteorites contain up to 45.9ppm Ruthenium, 8.6ppm Rhodium, 12ppm Palladium and 31.3ppm Osmium. (Buchwald, 1975; Hoashi et al., 1993; Mueller et al., 2010) These are optimal values, but the average M-type asteroid is still believed to contain up to 35ppm of PGEs, whereas on Earth, the typical high value PGE-ore contains only 10ppm. This means that M-type asteroids contains more than three times the PGEs than every single mine on Earth. (Ross, 2001; Bernardis et al., 2005) So far there are no concepts for the refining of PGE-ore in outer space, where the micro gravitation, and extreme temperature differences between noon and night side pose major difficulties for the recovery of pure noble metals, however considering that on Earth, even a third of the PGE concentration is considered an economically viable deposit, it is reasonable to assume that the processing of the regolith would be lucrative. With a mean density of 5300kg/m^3 one M-type asteroid of 100m diameter could contain up to 97 tons of PGEs. (Elvis, 2013) This amount would be worth over 2.8 billion dollars

if retrieved and sold under current stock market conditions. However not only M-type asteroids bear a significant concentration of PGEs. S-type asteroids, at least some of which are considered the parent bodies of the LL chondrites, could contain PGEs at about half the concentration to that of M-type asteroids. Palladium however, shows in at least some LL chondrites an abundancy which is even higher than in M-types (17.5ppm compared to 12ppm). (Sommariva, 2015)

7.1.4 Cobalt

Cobalt is essential for modern day society, and its applications are ubiquitous. It is used for high-performance alloys (alloys with excellent mechanical strength and resistance to corrosion and thermal creep deformation), for glass pigmentation, and even finds applications in catalysts. Especially since the lithium ion batteries have become popular in use during the nineties, the demand for this metal has risen extraordinarily. With only some 0.0029% of Earth's crust being cobalt, it is rather scarce for such a high demand. Due to this fact, it has turned out to be a highly profitable material for speculations with many hedge funds investing heavily into the mass storage of cobalt. (Welt, 2014) This increasing consumption rate in combination with the stockpiling of cobalt by hedge funds has led to a significant price increase of cobalt during the last couple of years. Since 2005 it doubled from 30$ a kilo, up to nearly 60$. (Infomine, 2017) With the international climate convention attempting to ban combustion engines until 2030, the consumption rate of cobalt, to produce the batteries necessary to cope with the increasing demand for electric cars, is expected to triple until 2030. (FAZ, 2010) Therefore, cobalt is most likely one of the prime targets for future asteroid mining operations. On Earth, the main ores of cobalt are cobaltite, erythrite, glaucodot and skutterudite, however most cobalt is produced by reducing the cobalt by-products of nickel and copper mining and smelting. This refining of the by-products however, involves a series of complex processes and reactions and results in a great environmental cost, setting free arsenates and other dangerous chemicals. (Shedd, 2007; Davis, 2000) The largest producer of cobalt is the Democratic Republic of the Congo, which in 2015 supplied 60% of the world wide cobalt production of some 32,000 tons. (Ober, 2018) Therefore, the price of the worldwide cobalt market relies heavily on the political situation in the DRC. This further increases the interest of asteroid mining companies to develop a significant alternative to the production line of cobalt, as it is a strategic resource, which will be reviewed in greater detail later.

While Earth has no native species of metallic cobalt, at least portions of the cobalt content in meteorites turned out to be in free state, however most of it is bound in minerals. The largest concentrations of cobalt can be found within iron meteorites with a percentage between 0.46-0.8%, and some LL chondrites even boast up to 1.57% cobalt content. (Buchwald, 1975; Malvin et al., 1984; Sommariva, 2015)

Compared to the average cobalt content amongst economically viable sources like silicate-nickel ore with 0.1% Co, where cobalt is refined out of by-products, or cobalt ore deposits with merely 1-4%, M-type and S-type asteroids can be considered profitable sources of this precious metal. (Entsiklopediya, 1978)

7.1.5 Rare earth elements (REEs)

Rare earth elements REEs are one of the most prominent group of elements potential miners and scientists alike are looking for in asteroids. They are comprised by yttrium (Y), scandium (Sc), and the 15 lanthanides; lanthanum (LA), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu). Based on their electron configuration, they are subdivided into the light REEs La-Nd, middle REEs Sm-Tb, and heavy REEs Dy-Lu. LREEs have unpaired electrons, while HREEs have paired electrons. Scandium and yttrium have properties not similar enough to classify it as either of the three sub-groups. Due to the overall similar chemical and physical properties of REEs, they can easily substitute for one another, making the refinery process of pure metal extremely difficult and costly. (Long et al., 2012; Trigo-Rodríguez et al., 2017) This further results in similar geochemical behavior, as all REEs are large-ion lithophiles, and most of them are trivalent and partition among mineral and melt-phases as smooth functions of their masses, called lanthanide contraction. Thereby the ionic radii decrease with increasing atomic mass. This makes them more resistant towards mutual fractionation than other elemental groups in geochemical processes. (Trigo-Rodríguez et al., 2017)

Contrary to their name, rare earth elements are not actually scarce in Earth's crust but widely distributed. Cerium, the most abundant REE occurs in some 43 ppm of overall Earth crust mass, and neodymium and lanthanum with 20 ppm each. However, they occur only in extremely small quantities and are only rarely concentrated in mineable ore deposits. (Long et al., 2012; Rudnick, 2005; Trigo-Rodríguez et al., 2017) This makes them extremely difficult to mine, as it is rather unusual to find them within concentrations high enough to be extracted economically efficiently. Their overall abundancy follows two different patterns. Firstly, those REEs with an even atomic number occur in larger abundancies than their odd-numbered counterparts, and secondly LREEs show a higher concentration within continental crusts, as they are more incompatible. REEs usually occur as phosphates, oxides, and carbonates within rock-forming minerals, instead of forming metals. There are almost 200 minerals known to contain REEs, however most of them only in such small concentrations, that they will most likely never become economically significant. The majority of REEs are stored within a very small range of minerals. The primary source of industrially used cerium, lanthanum, and neodymium are bastnaesite and monazite, whereas most HREEs are extracted from xenotime. (Harben, 2002; Brown et al., 2010) The formation histories of terrestrial REE deposits are extremely complex and involve various chemical, geochemical and physical processes, like weathering, hydrothermal-, and sedimentary processes. This makes the extraction techniques extremely variable for different ore deposits. At dry areas, both open-pit, and underground mining are used to excavate large quantities of material that later has to be grinded down and treated chemically to increase the concentration of REEs within the material. Thickening, filtering and drying produce rare earth oxides, which are then refined to extract the REE from their bearing minerals. (Brown et al., 2010) The sheer quantity of material that has to be excavated and treated chemically imposes a high environmental cost upon the producing countries.

The largest producer of REEs worldwide, the People's Republic of China supplied over 95% of REEs on the world market in the year 2009. However, due to environmental considerations and the will to conserve the precious deposits of the strategic resources, China has cut its production and exports of REEs severely within the last couple of years. (CNN, 2012) This has first led to an extreme increase in prices, that later fell again as new sources developed. For example; in 2015 one kilogram of dysprosium oxide cost 265$, which is only one quarter of its 2011 price of 994$/kg, but still 50% above the 2010 price, before China limited its production. (theGuardian, 2015) Thus much of the price volatility of REEs is not due to limited abundancy but rather caused by political limitations and geostrategic considerations. The development of a politically independent source or REEs would be most beneficial for the market, and prices, which would make the financial considerations of further asteroid mining that much less speculative. Still, not only political discrepancies influence the price of REEs, as almost every modern technology relies heavily upon them. They are used for the construction of lasers, spectrographs, batteries, nuclear reactors, TVs, cell phones, electronics, medicine, and even in catalysts. With these technologies becoming accessible to more and more people, the demand for REEs increases steadily.

To cope with ever higher demands, scientists have looked towards meteorites in the hope to discover new sources. Many have analyzed chondritic meteorites in the hope to find large REE-concentrations, however the results remain rather tricky to interprete. Many have found large Ce, and LREE enrichments within different types of chondrites, however for every positive REE anomaly, there are other results indicating the exact opposite. In some meteorites up to 100 ppm of Ce have been found, which would be more than twice the terrestrial abundancy, whereas in others, a depletion in REEs seems to have occurred. (Trigo-Rodríguez et al., 2017) The mineralogical abundancies are usually normalized to CI chondrites, which best represent overall solar nebula abundancies (Earth has overall chondritic elemental abundancies). The lowest REEs-abundancy is exhibited by the CM and CI chondrites, accompanied by the lowest degree of scattering values around 1. This is most likely due to them showing the lowest degree of metamorphization and the highest-, as well as the lowest porosity. (Dauphas and Pourmand, 2015; Trigo-Rodríguez et al., 2017; Macke et al., 2011) They are also the groups which experienced the highest degree of aqueous alterations (especially the CI-group). (Zolensky and McSween Jr, 1988; Zolensky et al., 1997) This low abundancy is explained by the fact that REEs have very low fluid/rock participation within aqueous alteration systems, enabling the remobilization of REEs. As a consequence, this would allow every single fragment of a parent body to exhibit extremely different abundancies of REEs, explaining the wide variety of REEs within meteorites. (Beitz et al., 2016; Trigo-Rodríguez et al., 2017) Stracke et al. (2012) found that REE concentrations can vary up to 5-times the analytical uncertainties within the same species of meteorites, indicating that a general assessment of REE abundancies would be very speculative at best. Most REEs however, seem to be stored within CAIs, the refractory inclusions in chondritic meteorites, as most laboratory analysis agrees. (Stracke et al., 2012; Trigo-Rodríguez et al., 2017) Overall, it can be said that while some asteroids may contain a major fraction of REEs, others of the same species do not, and only in situ measurements will be able to clarify which are lucrative destinations for mining operations.

Of course there are many more prospective materials abundant, as only the most prominent ones were reviewed in the previous sections. These were only the ones considered the most lucrative resources, the so called primary targets for future asteroid mining expeditions. As stated however, these are just the mean values expected on asteroid taxonomic classes. However, they do give a good impression of the riches floating in Near Earth space.

7.2 Asteroid selection

While indicating which asteroids may be interesting enough for a second look and further investigations, for the purpose of economically feasible ventures, rough estimations and proposals of minerals and elements abundant in taxonomic types of asteroids will not nearly be enough. Of course, the material abundancy and concentration will, in combination with the respective size and mass determine the overall maximum value, but leave us clueless about whether or not these resources will be accessible. Size, mass, density, spin characteristics, internal and surficial structure, composition, relative velocity (compared to Earth's), and orbital characteristics determine the cost and conductibility of these ventures. (Galache et al., 2017) While we have learned much about the chemical properties of asteroids by experimenting with meteorites, many of the physical properties, can so far be only remotely detected via Earth based surveys. To give a better impression of the obstacles laying ahead of asteroid miners, the remote diagnostic techniques and their applications, will be reviewed.

7.2.1 Diagnostics

Diagnostics From Earth, asteroids are generally seen in two different ways based on their own emissivity and their reflections. The sunlight they reflect, dominates the optical and near infrared (NIR) wavelengths between ∼0.5 and ∼3 microns. Their own emissivity derives from the sunlight that is not reflected, but absorbed by the usually rather dark surface of asteroids, heating it up, and thereby causing re-radiation of the energy at infrared wavelengths. For NEOs, this so called black body emission dominates from ∼3microns upwards. (Elvis, 2013)
There are several different techniques available to characterize asteroids, especially NEOs. Overall they form some sort of a pyramid, ranging from very cheap which provide only little information about the target, to rather expensive techniques revealing many of the asteroid's secrets. The cheap methods can due to their low price, easily be used on the majority of asteroids, covering great numbers at a time, while the expensive ones can only be afforded to be applied to smaller and smaller numbers, the more accurate they get. (Elvis, 2013) Which of them will be used, on which asteroids depends on what we want to know. Any interest in revealing more than a simple detection, or the orbital parameters of an asteroid, requires more photons to be caught and analyzed. As the amount of photons being caught is determined by the size of the primary mirror, and the observing time, increasing either or both is necessary to conduct a more sensitive survey. (Elvis, 2013) The resolving power R of a spectrum is $R = \lambda/\Delta\lambda$. $\Delta\lambda$ is thereby the width of the smallest resolved spectral bin, with being its central wavelength. A spectral resolving power of about 100 is enough for a spectrum, to be used as an asteroid characterization tool. An R of 100 is extremely low for optical astronomy, where the common spectra ranges in the thousands, and even 100,000 are realistically achievable. Being dependent on only low resolution for sincere scientific work has many advantages, as only few photons are required compared to other methods. Photometric bands require even fewer, as their resolving power typically ranges around 10.(Elvis, 2013)

7.2.1.1 Photometry

Photometry is the easiest applicable way to derive information about an object. It determines the color, which is in astronomy the difference in magnitudes between two photometric bands. It gives a rough information about the shape of their spectrum. For example the 'Eight-Color Ateroid Survey' demonstrated the diagnostic value of optical broad band photometry for science evolving around asteroids (Zellner et al., 1985) It allowed NEOs being roughly classified into types by the shape of their spectra. The first taxonomic classification system by Tholen (1989) was established using data derived by this method. Only four of the SDSS bands proved to be enough to classify asteroids in a few sub types, as long as the photometric errors range in the lower percentage. (Tholen and Barucci, 1989; Elvis, 2013) While this is sufficient for keeping S- C- or D-type asteroids apart, it is not enough to separate more similar asteroid types such as E-, M-, or P-type objects. (Carvano et al., 2010; Ivezić et al., 2001; Elvis, 2013)) With the magnitudes exhibited by NEOs, exposure times for photometry are rather short, making it extremely time and thereby cost efficient. A single 1m telescope, solely dedicated to the characterization of NEOS can roughly classify hundreds of objects a year into S and C types using only photometry from the SDSS bands. One minute of exposure time would entirely suffice for a clear detection, and 5 minutes would already reach an accuracy of 3%. (Elvis, 2013) There are many observatories which have some telescopes partially dedicated to do photometry of asteroids, most of which observe in a single broad optical band, deriving light curves, but don't deliver multi-band information for taxonomic classification. The Palmer Divide observatory in California is currently one of the leading sources of asteroidal light curves in the world. The Palomar Transient Factory, using a 1.5m and a 5m telescope provides the option for a fast follow up investigation of the objects delivering multi-color photometry data. (Elvis, 2013)

7.2.1.2 Optical and near infrared

Optical and near infrared spectra make up the next level of the pyramid. NIR spectra spanning the 0.5-2.2micron bands, are typically used to classify asteroids into the Bus-DeMeo system. This endeavor requires merely R$\sim$100 spectra, making it rather easily applicable. (DeMeo et al., 2009; Elvis, 2013) Ranging between 1% and 5% of the flux at their wavelengths, the respective diagnostic absorption features are relatively weak. This makes a high signal to noise spectra ($S/N > 10$ per pixel) necessary to derive the needed information. If conducted by ground-based surveys, optical-NIR spectra has two severe limitations. Firstly, as the majority of asteroids have only ever had one single spectrum taken, information about the variety of surficial minerals remains very limited, since only multiple spectral analysis can give insight into the complexity of surface composition. Secondly, and more grievously, repeatedly spectrally observed asteroids showed a variety in spectral shapes on different occasions. The difference in spectral shapes can be of such an extent, that they would even have to be classified into different classes, depending on the respective observations. (Moskovitz et al., 2012; Elvis, 2013) This uncertainty in the spectra is further increased by the both strong and extremely variable NIR background on Earth, depending on various factors, and the inherent lack of quality in the characterization of standard stars. (Elvis, 2013) While such single spectrum analyses can be used for researching large quantities of samples, where the shier amount of data averages out the errors, it is not nearly exact enough for asteroid mining ventures. (Elvis, 2013) Such cost intensive endeavors would require a lot more certainty about the properties of a target object than these methods could possibly provide. Otherwise, a single mining expedition may need a variety of potential targets in the hope of covering the respective properties of at least one of the asteroids. This however would result in much higher cost, as the additional distances, which have to be covered will require a lot of travel time by the machinery. The asteroid spectrographic characterization rates are limited by the sensitivity of the NIR spectrograph. A survey with an optimized program conducted on a telescope solely dedicated to the classification of asteroids could potentially sustain a pace of some 2000 NEOs per year. To reach such a high rate, an average of about 10 spectra taken during each night with adequate conditions would be required. Assuming an average 10-hour night, this would allow for exposure times of about 45 minutes with an additional 15 minutes time to derive the calibration data (mostly well-measured standard-star spectra), for every single spectrum acquired. (Elvis, 2013) Such timeframes are reasonable, as for example the SpeX spectrograph usually needs between 30 and 60 minutes of exposure time, as it tracks NEOs across the background field of stars. One of the largest optical-NIR spectroscopy surveys currently conducted is the MIT-UH-IRTF Joint Campaign for NEO reconnaissance. The program uses the NASA 3.3m Infrared Telescope Facility (IRTF) on Mauna Kea Hawaii, in combination with the SpeX spectrograph. Within only nineteen nights between May 2011 and May 2012, it managed to aquire spectra of 84 NEOs, which at the time was about 10% the NEO discovery rate. (Elvis, 2013) The SpeX spectrograph, used on this survey, can classify NEOs as faint as $V{\sim}17.5$. (Elvis, 2013; Binzel et al., 2006) Unfortunately, most of the NEOs discovered, lie beyond its reach, as the majority of NEO population range around $V{\sim}18\text{-}21.5$. Only some 30% are at least sometimes brighter than $V=17.5$. (Elvis, 2013) Spectrographs, which have been developed more recently, can if used with larger telescopes, obtain spectra of far fainter objects. The Folded-port Infrared Echellette (FIRE) on the 6.5m Magellan telescopes for example, can obtain spectra from objects of $V=20$ with merely one hour of exposure time. With such a range, over 96% of all NEOs currently discovered are accessible for spectrographic analysis. (Elvis, 2013; Simcoe et al., 2010; Moskovitz et al., 2012) Unfortunately, observing time on such large telescopes are in high demand and therefore rather scarce, leaving almost no operation time for the characterization of asteroids. Still, being technically able to spectrographically analyze such faint objects is of advantage, as this somewhat loosens the otherwise tight schedule for observations. Over half of all NEOs stay brighter than $V=20$ for at least three months, whereas only about 15% of NEOs stay brighter than $V=17.5$ for the same period. (Elvis, 2013) These larger windows of opportunity make it by far easier to fit a schedule for the spectroscopic observation after discovery, for example to evade a full moon, which would severely decrease the spectrographic sensitivity. (Elvis, 2013) Another way to increase the sensitivity of optical-NIR spectrophotometry is to reduce the NIR sky-background, which can-be achieved by new NIR technology. The background is produced by thousands of emission lines, emitted by OH molecules within Earth's upper atmosphere. Even the use of nearby standard stars as calibration reference, is complicated by these emission lines greatly varying on both hour, and minute timescales. They create an average background noise of 20-30 dB, which is equivalent to 5-7.5 magnitudes. With these emission lines being eliminated from observation process, a single 1m telescope could work as sensitive as a 10m telescope does with the background. With less than 0.1nm in wavelength, the emission lines exhibited by OH molecules are generally rather narrow, and thus, could potentially, be selectively removed from the spectrum, without having any negative effects on the signal measured from the asteroid. With good progress made in the development of FIRE, it now has a resolving power of R$\sim$6000, allowing for the removal of hundreds of OH emission lines. With so-called OH suppression, which is of great importance for many cosmological studies, a gain of 20dB has been achieved. After that mark, other background producing processes become dominant, only some of which are understood. (Elvis, 2013; Sullivan and Simcoe, 2012) However, further progress in this field of study can be expected within the next years. The OH emission lines could also theoretically be avoided, simply by basing the telescope in space, however the extreme prices make the first approach preferable, as it is by far cheaper.

7.2.1.3 Thermal infrared photometry and spectroscopy

Thermal infrared photometry and spectroscopy is one of the most sophisticated, most precise and therefore most cost intensive ways to measure the characteristics of asteroids. Since Earth and its atmosphere are warm enough for themselves to emit in the thermal infrared, both create a strong background. For ground-based observations, there are only three thermal infrared windows of transparency in Earth's atmosphere: the M-band at 5 microns, the N-band between 8 and 13 microns, and the Q-band at 20 microns. (Elvis, 2013) The N-band is the most commonly used band, as it lies within both the widest and most transparent window of transparency, making it extremely sensitive. For the purpose, of measuring an asteroid's surface temperatures, it requires merely R$\sim$10 across the entirety of the 5 microns wide N-band. To measure the surficial composition of an asteroid, or to reveal details such as dust size distribution, R$\sim$30 is required, which is still comparably low. (Elvis, 2013; Vernazza et al., 2010) Ground based thermal infrared surveys however, have rather low applicability, as only a small minority of NEOs ever come close enough for observation, simply because they are to faint for this technique. This background related limitation in applicability, can be coped with, by basing the telescopes in space, which on the one hand takes away most of the difficulties linked to Earth's temperature, however makes the entire endeavor extremely costly. Still, the extremely low background in space, in combination with the option to cool the instruments below 40K, make an extremely large difference in both sensitivity, survey speed. For example the space-borne NEOWISE survey, was about 300 times faster than the 8m Gemini telescope. In space, a single detector can capture the entire 0.5-10 micron spectral range, without the gaps that would be produced by the atmospheric background. (Elvis, 2013; McMurtry et al., 2013)

7.2.1.4 Radar

Radar observations can give precise information about both, orbital details, and the shape and rotation axis of NEOs. The best radar data have an effective resolution of a few meters and gave scientists spectacular insights into the characteristics of asteroids. Unfortunately, even the largest radio dishes in the world can reach only a small minority of all NEOs, which come as close as 0.05-0.1 AU. (Elvis, 2013; NASA, a) This is due to the outbound signal being attenuated as $1/r^2$ on the way to the asteroid, and $1/r^2$ on the return. This way, a share of only $1/r^4$ of the signal emitted comes back to Earth. While they may be applicable to a few NEOs, radar observations are not that great for bulk characterization, and are generally limited to pose as a calibration tool for other previously described scientific methods. (Elvis, 2013; Howell et al., 2012; Mainzer et al., 2011) This extreme decrease in signal strength makes extraordinarily strong high power emitters necessary. For example: the 70m Goldstone, and the 300m Arecibo dishes, which are the main facilities used for radar astronomy, use up to one megawatt transmitters. The large quantities of energy required for their operation make fuel cost an important factor in the price calculations, and pose a rather strong limit to the further increase in coverable distance. To reach twice as far into space, the energy consumption of the facility would rise by a factor of 16. Still, NASA funded radar observations at both dishes, supporting the study of 20-30 NEOs per year, which increased in 2012 to 80 NEOs due to fuel cost savings. (Elvis, 2013; NASA, 2017b)

7.2.1.5 Optical and infrared interferometry

Optical and infrared interferometry allows the reconstruction of images by combining images provided by several small telescopes, to the resolution of a single large one. As the limit in maximum angular resolution of every telescope is given by diffraction by a fixed wavelength, a larger aperture increases the resolution of images at a fixed wavelength, while a shorter wavelength increases the resolution for a fixed aperture size. When two small telescopes have a considerable separation between them, interferences occur between their light beams as they move in and out of phase while surveying. Therefore, using multiple small telescopes allows the production of images of the same resolution, as a single large telescope with the size of their separation could provide. (Elvis, 2013) While this technique has long been used on radar observations, its application on smaller wavelengths such as the optical or infrared is by far more complicated. (Elvis, 2013) Still, there are examples of facilities using this method, such as CHARA in California, or the European Southern Observatory (ESO) Very Large Telescope Interferometer (VLTI). The VLTI MID-infrared Interferometric instrument (MIDI) obtains images at a resolution of 20 milliarcseconds in the N-band. (Elvis, 2013) While this is about 10 times better than the Hubble does in the optical regime, it still comes down to only 1.5km resolution within a distance of just 0.1AU, which is even worse than radar. Being additionally limited to a brightness of V=14 or more, VLTI-MIDI can only occasionally be used for the characterization of NEOs. (Elvis, 2013; Delbo et al., 2009)

7.2.1.6 Astrometry

Astrometry is the accurate measurement of the position an object has on the sky. Due to the Yarkowsky effect, small changes in orbital parameters, and therefore differences in the calculated and real position, are continuously occurring. This enables us to measure the magnitude of the Yarkowsky effect on certain celestial bodies. Despite the net force deriving from the effect is as low as 10^{-4}AU/Myr, it has first been confirmed by precise radar measurements, and could later be observed by very sensitive astrometric measurements. (Elvis, 2013; Chesley et al., 2003) Exact knowledge about the Yarkowsky effect induced orbital changes are necessary to predict an asteroids location for decades in advance, which in turn is absolutely vital to not lose it again as soon as it was found. Further, astrometry gives hints for other forces to be present if the orbital change measured is larger than the Yarkowsky effect could ever cause. This could for example indicate a mass loss from the asteroids surface. Unfortunately, the applicability of astrometry on bulk characterization remains poor, as normal astrometry is unable to detect the influence of the Yarkowsky effect on a decade timescale. Nugent et al. (2012) for example, were only able to detect the Yarkowsky effect in 54 out of 1250 observed NEOs.(Elvis, 2013; Nugent et al., 2012) Even the ESA GAIA mission, with its milliarcsecond resolution on a telescope area equivalent to a 0.5m diameter mirror, will most likely not be able to detect the Yarkowsky effect in more than a handful of NEOs. (Elvis, 2013; Mouret and Mignard, 2011) Still, astrometry is an important source of calibration data, and can lead to major conclusions in combination with data supplied by other methods.

7.2.2 Discovery

Finding NEOs requires surveys with sensitive telescopes. However, to be time and cost efficient, these surveys also need as wide a field of view as somehow possible, to maximize the portions of the sky observed, and thereby the number of NEOs detected during each exposure. As NEOs move comparably fast across the solar system, and can be rather close to Earth (making them move even faster across the observed field of view) single exposures cannot take longer than a few minutes. Otherwise an elongated image would be created. While on the one hand such a long drawn signal would most clearly identify a moving object as such, it would still strongly reduce the survey's sensitivity, as the signal would be spread over multiple pixels. (Elvis, 2013) As no images are flawless, false detections can happen due to for example cosmic rays coming through the camera, producing blemishes and such on pictures, which are gone again in the next. To prevent these apparent detections from happening, surveys usually require between 3-5 detections in a row for the object counting as confirmed asteroid. (Elvis, 2013) The search for NEOs commences with both, ground-based and space-borne surveys. The ground-based ones are only really practical in the optical band. This is because of the high atmospheric transparency in this wavelength regime in combination with the low background, and the relatively low cost involved with the acquisition of large optical detector arrays and their operation. However ground-based surveys have also severe limitations on their practicability. As every telescope used, can only cover its own hemisphere, and only by night, the need for multiple telescopes co-operating arises, to cover the entire night-sky at the same time. (Elvis, 2013) Surveys would have to last at least a decade to be able to catch the major part of asteroids in more than one apparition. This is because 98% of NEOs with known orbital parameters swap hemispheres over a decade interval in their apparitions, due to their inclination and Earth's tilt out of the ecliptic. (Elvis, 2013) Additionally, as mentioned before, the most easily from Earth accessible asteroids are those with the most Earth-like orbits, and as explained, these asteroids need a near 1:1 mean motion resonance with Earth and therefore have extraordinarily similar rotational periods in order to be stable. Therefore these objects fall behind, or catch up only extremely slowly to Earth, making the time between their apparitions (also called synodic period) very long, being estimated to range in the decades. This means that a 10-year long survey would miss these Earth co-orbitals. (Elvis, 2013; Vereš et al., 2009)

7.2.3 Orbits

Every closed orbit is an ellipse, and characterized by the six orbital parameters, as described in the classification chapter. An accurate orbital characterization is vital to claim an asteroid or other celestial body detected, as can currently be seen with the proposed planet nine. If the orbit of a newly found asteroid is not well enough determined for it to be found again by the next time it becomes visible during its next 'apparition', it will be lost again as quickly as it was discovered. (Elvis, 2013)

In most cases, orbit determinations of NEOs are a rather easy task in comparison to size or mass estimations. Orbits well enough for the prediction of apparitions a few decades in advance, can be achieved with rather modest means, as 1-2m diameter Earth based telescopes are sufficient, fairly common and comparably cheap to use. The orbital parameters are then calculated at the Minor Planet Center of the International Astronomical Union, which is located at the Harvard-Smithsonian Center for Astrophysics. (Elvis, 2013; Minorplanetcenter, 2017) Thereby a logarithmic uncertainty code, U, ranging between 0 and 9 is assigned, indicating the uncertainty in position of the asteroid in question after one decade. An uncertainty factor of 6 for example, would mean that after 10 years, there is an uncertainty of 2.08 degrees for the location of the asteroid. Such a high uncertainty would make the picking up of the body extremely hard, so it is virtually lost. Follow up imaging with telescopes of a few arcminute diameter field of views would require $U \leq 5$, to have an uncertainty of less than two arcminutes after 1 year. Spectroscopy would need $U \leq 2$, in order to achieve less than two arcseconds of uncertainty after 1 year. Overall, about 75% of all NEOs have their orbits determined with an uncertainty parameter of less than two. (Elvis, 2013; Minorplanetcenter, 2017) These U-values are strong confidence limits, correlating with 3 sigma uncertainties in location. This means that some 99.7% of the times, the asteroid does lie within the radius of predicted position. (Elvis, 2013) Further advancements of the algorithms for the derivation of asteroidal orbits may significantly improve the data situation and reliability, as they take into account more and more uncertainties from different sources and correlated errors within each data source. (Elvis, 2013; Baer et al., 2011) However, as more resources are dedicated to the discovery of NEOs than the re-location, which would be necessary every couple of years, as the uncertainty of position rises with the time going by since last visual contact, many objects which have already been discovered fade away into the obscurity of uncertainty again. This goes so far as to be described as one of asteroid mining's larger problems, which will be reviewed later, by many scientists.

7.2.4 Size and mass

Deriving a body's size depends mostly on the knowledge of the surficial albedo, giving the reflectance fraction of the incoming sunlight. As most asteroids are rather dark, only small portions of the photons reaching their surfaces are being reflected, while the larger fraction heats the asteroid. While the magnitude of the optical wavelengths surveyed depend primarily on the albedo, the magnitude of the thermal infrared emission measured depends mostly on the respective size of

the body. (Elvis, 2013)
The geometric albedo, p_V, is measured at a phase angle of zero, while the Bond albedo A_B is the fraction of input sunlight on the asteroid's surface that is reflected. The Bond albedo thereby is the average albedo measured over all observing phase angles. (Elvis, 2013; Harris and Lagerros, 2002) Within the NEOs group of asteroids, Bond albedos span over the range of about 5. Therefore, without further knowledge of the observed asteroid's surface beside the optical measurements, the sizes derived will have an uncertainty factor of $\sqrt{5}$, and the volume will be uncertain by a factor of 11. Such an uncertainty would be unacceptable for any mining ventures, as that can most easily be the difference between the profit or loss of billions of dollars. Within a specific taxonomic type however, albedos cover a narrower range of distribution, for S-type asteroids for example, residing somewhere near a factor of 1.4. (Elvis, 2013; Thomas et al., 2011; Mainzer et al., 2012) As the optical band is the most technologically developed to study and can be done from Earth, this approach costs by far less than any alternative and is applicable in bulk. (Elvis, 2013) Most of the NEOs orbiting close to 1 AU re-radiate their absorbed solar energy at an equilibrium black body temperature similar to Earth, around 300K. This emission peaks at $\sim$10 microns, but is strong throughout the $\sim$5 to $\sim$50 microns band, called the thermal infrared. As a black body of 6000K like the sun peaks around 0.6 microns, which is well within the optical regime, NEOs stand out clearly in the thermal (mid) infrared band. (Elvis, 2013) If the surface temperature of an asteroid is known, the observed flux from the surface gives the size of the emitting surface area, and thus tells us the diameter of said object. To get the surficial temperature of an object, at least two, but preferably more wavelengths are necessary. With the size and the magnitude H of the object, the albedo can be calculated rather easily. The thermal inertia can still alter this simple calculation to a small, yet significant extent, as once the re-radiating surface is out of direct sunlight, it still radiates in the thermal infrared, being out of thermal equilibrium with its surrounding environment. While this effect can enlarge the apparent area of the asteroid, it can be very well coped with careful thermophysical modelling of the object. (Müller et al., 2011; Elvis, 2013) Especially the Near-Earth Asteroid Thermal Model (NEATM) by Harris, (1998) is often used for these measurements.(Harris, 1998) It seems rather fortunate that the wavelengths at which NEOs usually peak (between 8 and 13 microns) lie well within the clean and broad N-band, a window of transparency in Earth's atmosphere. As this temperature is rather much the same as Earth's however, the telescope and mirrors respectively emit in the same wavelengths, creating an extremely strong background for these observations, crippling the sensitivity of the measurements. Additionally, thermal infrared measurements are somewhat technically challenging and rather complicated to do sensitively, and therefore are best conducted via space-borne telescopes to escape Earth's thermal background. This makes them

rather expensive though in comparison with optical surveys, further limiting its application possibilities. Luckily, sizes need not necessarily be measured for every single NEO, as they can be discovered in the optical regime, and size/mass are only necessary to derive for rather promising candidates, which can be done later. (Elvis, 2013)

NEO sizes can not only be calculated based on their thermal infrared flux, but also estimated by their absolute optical magnitudes, a common scale with all objects being placed at the same heliocentric distance on the same illumination conditions. The observed magnitude in contrast, depends mostly on the heliocentric distance and whether they are fully illuminated or observed under a lesser favorable phase angle (meaning that they are only partially illuminated) while being observed. (Elvis, 2013) The absolute magnitude H, that is usually used on most asteroids including NEOs, would thereby theoretically be measured from an object at 1AU at a phase angle of 0°. (Elvis, 2013; IAU, 2015) The H magnitude is therefore a notional reference magnitude only, as solar system geometry never allows for a NEO to be observed under such conditions. It is defined in the Johnson/Cousins V band magnitude, which is centered on 0.55 microns, and spans a 0.09 microns wide band. This is important, as for other wavelengths different magnitudes would be produced, since asteroids tend to have differently shaped spectra. The diameter D of an asteroid with given magnitude H and geometric albedo p_V is defined as: $D = 1329 p_V^{-0.5} 10^{-H/5}$ (Elvis, 2013; NASA, b) The size of a NEO only roughly defines its mass, as asteroids span a considerable range of different densities, and tend to be filled with voids, empty cave-like spaces. The fraction these voids hold of the entire volume is called porosity. Usually the larger (km-sized) asteroids tend to have a lower porosity $\leq$0.1, whereas smaller asteroids span a wide range of porosity from 0.1 to 0.5 or even up to 0.7. (Baer et al., 2011; Elvis, 2013) These large differences of porosity even within species renders the determination of an asteroids mass uncertain by a factor of 2-3, even if their size has been well measured beforehand. The porosity of asteroids mostly depends on the formation history and the evolution of the body. Extremely high porosity values are thought to be the result of almost destructive collisions where the body was at least partially fractured, yet the gravitation kept the fragments together which filled the body with voids. So far, the only way to examine the porosity of asteroids were their meteoritic counterparts, and thus especially the 100m diameter asteroids have seen little investigation in this area. (Elvis, 2013) It seems likely however that the porosity of these objects could include very high values. This makes not only mass determination extraordinarily complicated and besmirches it with possibly extreme inaccuracies, but poses also major threat to the excavation tools used by asteroid miners, once missions are ongoing, as nothing is as dangerous to drills as empty spaces in the material.

Finally, the mass of NEOs depends on the density of the materials it is composed of. These densities are purely derived from meteorite samples, and therefore suffer yet again the uncertainty of the meteorite/asteroid linkage. Iron meteorites of a purely Fe-Ni composition have densities ranging in between $7.3 - 7.7$ g/cm^3, whereas the common silicate meteorites made up of pyroxene and olivine typically lie around 3.2 4.37 g/cm^3. Clays usually reside near 2.2 2.6 g/cm^3 (Britt et al., 2003; Elvis, 2013) These differences of a factor of up to 3.5 can, as mentioned earlier, be neglected by spectroscopically putting the asteroidal material into one of the classes, but the uncertainty is still considerable. In addition to these problems, meteorites tend to show signs of micro-porosity, further reducing their overall densities compared to the compact densities measured. (Britt et al., 2003; Elvis, 2013)

The only reliable ways to determine an asteroid's mass is to either find a binary, where the gravitation and the rotation/orbiting periods per definition define the mass of both objects, or to directly measure the yarkowsky effect, which also depends mostly on the mass while all other parameters are easily measured. (Elvis, 2013) Both of these ways however, are unfortunately only applicable to only the slightest minority of NEAs, and therefore the masses can only be more or less roughly estimated based on mass and taxonomic type, until in situ measurements are conducted, which would be necessary to derive values that are not only astronomically accurate, but economically feasible.

7.2.5 Rotation periods and internal structure

The rotation periods and aspect rations of NEOs can be determined based on their optical variability. This is done using data of their brightness time series, called light curves. As bodies usually tend not to have a homogeneous albedo distributions across the entirety of their surfaces, some parts are darker than others, having them reflect less light to our direction as long as we see that specific area. As the shape of the light curves represents the flux from the surface at each time, the period of one rotation can be found from the time it takes the light curve to repeat its shape. For a symmetrical body the rotation period would be twice the repeat time. The aspect ratio of an asteroid, the ratio between the different dimensions, is generally at least roughly given by the amplitude of the light curve. (Elvis, 2013) The various rotation periods of NEOs can vary from merely a couple of minutes, to over 10 hours or more. Generally only the smaller NEOs have rotational periods of less than one hour, while larger asteroids tend to have lower spin periods. With larger diameters the same angular momentum would result in higher absolute velocity on an asteroids surface, throwing off large quantities of its loose regolith centrifugally. The same counts for faster rotation periods on smaller asteroids, which can still happen. (Elvis, 2013; Pravec and Harris, 2000) This distribution of rotational

periods over the different sizes of asteroids can be understood as good indications, that smaller asteroids are generally more likely to be monoliths, whereas their larger counterparts are more likely to be rubble piles. (Elvis, 2013) This is so far one of the only ways to remotely gain information about the inner structure of asteroids. Despite both extremely fast and slow rotations having been detected, only few small NEOs have spin periods of less than a few hours. This is most likely due to the YORP effect easily spinning them up, as it has the most severe effects on small low mass objects. (Rubincam, 2000; Elvis, 2013)
If the asteroid is not alone, but accompanied by a smaller secondary body, it is called a binary. These are identified by seeing eclipses in the light curves, whenever the secondary body shadows the primary, and observed asteroid. If this is the case, then the bodies' masses can easily be determined by using Kepler's laws. However only some 15% of NEOs appear to be binaries, which can at least partially be due to the lack of sensitivity to small secondaries. This could be changed by the Kepler mission, which could detect larger fractions of binaries with its high precision photometry. (Elvis, 2013) This could enable us to determine more NEO masses rather cheaply. The overall structure and morphology of NEOs can be determined by using tomographic techniques, if their light curves sample at least ten different phases during one period, and span a number of spin periods accurately (~1-3%). (Hanus and Durech, 2010; Elvis, 2013) These are so called tumblers, asteroids which do not rotate around one of their principal axes. They point different surficial areas to Earth with every rotation. Therefore they allow us to better reconstruct their tomographic three dimensional shapes. Genetic algorithms and other newer data analysis techniques overall enable us to get more and more structural information from light curves. The new techniques can be tested and validated on objects where the results can be compared to spacecraft in-situ images or radar measurements. (Bartczak and Marciniak, 2012; Elvis, 2013)

7.2.6 In situ analysis

As was pointed out in the previous sections, remote observation realistically stands no chance of ever supplying us with the necessary quality of information about the asteroids surface, and internal properties. While being able to deliver the information needed to decide which objects could be lucrative targets, all these techniques fail to give insight detailed enough for any kind of mining machinery to work with. Therefore, asteroid prospective needs to go further than astronomical methods and techniques to provide detailed compositional information. Local characterization is thus the next logical step towards asteroid mining. Despite remotely acquired characterization of asteroids being only astronomically accurate, it is still vital since it limits the number of asteroids that have to be visited. Some NEOs can be ruled out as possible targets for example due to their orbital parameters making them unaccessible for spacecraft, or their rotational periods being too high for machinery to find a hold on their surface. Local characterization is necessary to fill the gaps in knowledge. Especially masses can usually only accurately be determined in situ, which is done by using tracking telemetry on robotic spacecraft visiting asteroids. (Kistler et al., 2010; Elvis, 2013) X-ray and gamma-ray spectroscopy can be used in situ to detect any surficial resources, whereas optical imaging can be used to derive the density of an asteroid. Contact measurements such as planned collisions can provide information about the structural constitution of a NEO, while bore-holes can additionally give further information about the mineral content within an asteroid's interior. (Elvis, 2013)

Direct contact further brings up additional techniques. Direct impacts, as is planned in the DART mission, can be used to measure surficial material strengths, and could potentially even penetrate deep enough to reach regions where volatiles are still present. Using a lander to gently reach the surface of an asteroid allows more sophisticated measurements to be conducted. Laser created plasmas can be used to probe the surficial composition of single only mm-sized areas, analyzing it spectroscopically, as is done in the ChemCam instrument. (Elvis, 2013; Maurice et al., 2005) Mass spectrometers like the SAM instrument can be used to gather detailed information about the regolith molecules. (Mahaffy et al., 2009) The large variety of instruments aboard the Mars Science Laboratory Rover Curiosity, for example shows the wide field of contact instruments available for such missions. (Grotzinger et al., 2012) While the cost and mass of Mars rovers alone precludes the mass production of this type of robots, they can be used to further our knowledge about general characteristics of asteroids, by using similar machinery on single objects. Additionally, the landings alone would generate a considerable amount of know-how for asteroid miners, as there is not so much difference in the landing procedures of a 1kg rover, or a fully equipped mining robot. Generally, science has to solve many problems asteroid miners would later encounter beforehand for detailed in situ analysis, such as the anchoring required for the drilling of boreholes. (Daniels, 2013; Elvis, 2013)

7.2.7 Next steps

Single missions to asteroids, as NASA, ESA, and JAXA are conducting, are important in order to figure out how the general mechanics and properties of asteroids are working, and learning how to optimally conduct space probes on NEOs, however they do not necessarily provide the information that asteroid miners require on every single object. Every asteroid is unique, with its own composition, structure and properties. Not every asteroid is as resource loaded as would be required to make a mining venture financially feasible. To find a single NEO in the top 10th percentile in the resources that are sought for, at least 10 asteroids would have to be investigated solely dedicated to derive the information asteroid miners are looking for. However the possibility of just being unlucky has to be considered, as the binomial distribution of finding at least one top tier asteroid in ten trials is only 65% In order to reach at least 90% confidence, 22 asteroids will have to be investigated and for 99% there are already 44 missions necessary. (Bevington and Robinson, 1992; Elvis, 2013) Thus, 44 of the remotely already characterized as promising candidates would have to be visited with space mission, to have an economically acceptable chance of finding at least one target for a mining venture. As the transit times between two of the rather rare promising candidates are likely to be at least a year, even a dozen dedicated spacecrafts would simply take too long to locate a mining target. (Elvis, 2013) A parallel approach is necessary, thus the need for multiple small missions arises, in order to find a number of potentially lucrative targets for exploitation. An entire fleet of space probes swarming out into the solar system could investigate a series of NEOs simultaneously. Since the cost of obtaining the information necessary cannot be more than the exploitation of a valuable asteroid would justify, it needs to be limited to a modest fraction of the resource value ultimately retrieved. Assuming the cost of information gathering being limited to moderate 10%, the nominal ∼5million value of a single PGM-rich 100m diameter NEO would cap the prospecting cost at some 500million dollar. This means that a series of cheap-to-produce, and small spacecraft with only the most basic instruments on board would have to be launched rather cheap. (Elvis, 2013) Taking for example the OSIRIS-Rex mission, which as a New Frontiers class mission has an approximate cost of some 800million dollar (not even including launch cost), the price for a single craft will have to be decreased considerable. (Lauretta and Team, 2012) Fortunately, the robotic characterization missions would not necessarily have to return any samples to Earth, if they analyze the composition in situ, which reduces the price considerably. If the necessary information can be gathered without any direct contact between the spacecraft and the asteroid, this would further lower the price. Still, the probes designed for this purpose would have to be significantly smaller and cheaper. (Elvis, 2013) To keep the probes as small as somehow possible a minimal set of instruments, necessary to derive all the required data, needs to be defined. This could be limited to only a radio tracking device, an optical imager, and possibly an X-ray imaging spectrometer. (Elvis, 2013)

Once there is a demand, it is only a matter of time until it is met, and thus this need has already been recognized in the industrial sector. Planetary Resources is already developing the Arkyd satellite series and Deep Space Industries is currently working on the design of the cubesat-based satellite called Firefly. The firefly concept proposed, was a 25kg satellite designed to do mineral surveys. To reduce costs, swarms of them would be launched in rockets they share with larger communication satellites. Proposed in 2013, Deep Space Industries projected a second design DragonFly, a larger sample return vessel, to be launched in 2018, with the object to transport up to 150kg of asteroid material back to Earth. (NASA, 2013b) A later concept was to design a 'mothership' that can carry up to a dozen extremely small survey satellites called nanosats beyond Earth orbit. The mothership would be around 0.91m∗0.46 in size and about 150kg in mass. The nanosats would be cubes with a side length of roughly 15 cm. The mothership would provide the deep space communication capability between the nanosats and Earth. (Woo, 2014) The Arkyd satellite series of Planetary Resources was intended to package a number of non-optical satellite technologies when the model was revealed in 2013, however when the first attempt was made to test the satellite it was destroyed in an explosion during launch in 2014. A second attempt to test the design was a full success in 2015, resulting in the validation of avionics, attitude determination, control system, and propulsion system. (Wall, 2015) Operating small spacecrafts on distances of interplanetary scale however poses some major challenges, which will have to be dealt with. Firstly, propulsion is a problem that is not so easy to be solved, when one of the most important criteria is a considerably small weight of the probe. The propulsion and therefore its fuel, necessary to travel across the solar system for years, visiting many different NEOs in a series, could be provided by rocket-on-a-chip technologies like microfluidic electrospray propulsion (MEP), which rely on solar energy. Probably less concerned with the environment, radioisotope-powered thermos photovoltaic systems (RTPV) outpower solar energy based technology in terms of propulsion by far, however solar energy is currently considered more realistic in terms of anticipated technology. (Elvis, 2013; Mueller and Mueller, 1997; Howe et al., 2012) Secondly, communication becomes really tricky once certain distances are reached, and the size of the spacecraft does not allow an onboard communication system powerful enough to send signals across half of the solar system. Communication over distance of AUs requires not only high power transmitters, but also antennae over 34 meters long, like NASAs Deep Space Network, to receive the weak signals. (NASA, 2013a) One possible solution to this problem could be to set up a network of small transponder satellites within the inner solar system to establish some sort of solar system internet, carrying signals around the sun. (Elvis, Landau et al. 2012) Another way to cope with this challenge could be the development of the square kilometer array, a technology that could track several probes at once. With a price goal of one billion for the entire kmÂš area, a 100diameter antenna covering about 1% of the entire area should cost somewhere around 10million dollar. Other, more careful studies suggest that an X-band only facility would cost around 30-40million dollar. (Elvis, 2013; Jones, 2006) Thereby more than one system would be needed, to enable continuous communication over such large distances.

An alternative to radio communication may be an optical, laser-based communication system, as it would require only moderate aperture telescopes as receiver ground stations on Earth. However, pointing near the sun may be necessary for certain operational stages, which would lead to an extremely high background for the receiver. Luckily, the very narrow laser bandwidths help mitigating this problem. If wavelengths were to be chosen which lie well within solar spectral absorption bands like the 589.29nm Na H+K, or the 656.28nm HÎś, communication interferences could further be limited. (Elvis, 2013) The upcoming optical sieve technology might help by providing large optical mirrors for the transmission of optical signals from small satellites, with very low mass. (USAFA, 2010; Elvis, 2013) The largest problem for any optical communication system however, is to actually achieve the extreme pointing stability of below arcsecond precision necessary for the beam to intercept Earth.

7.2.8 Implementation

The Implementation of such a titanic task requires both, a plausible cost estimation, and a realistic time scale, based on which these operations can be carried-out. A first step would be to increase the rate at which the spectroscopic characterization of NEOs is conducted, significantly. If the rate of characterization could be increased up to 2000 per year, the 20,000 NEOs larger than 100m, could be analyzed within a decade. However, such a high rate is highly unlikely to be achieved on an established route, as all large telescopes are currently funded for astronomical research only, and their observing time is already oversubscribed by a factor of three or so. (Elvis, 2013)

Thus, the fastest and probably the most realistic way to take 2000 NEO spectra every year would be to build at least one new large telescope, solely dedicated to this purpose. A rather cost efficient design which could be used to offer an approach that is not too cost intense, is the 10m Southern African Large Telescope (SALT). (Elvis, 2013) In the year 2000 it was built for less than 30 million dollar, including an imager, as well as a spectrograph. The low cost is due to the use of a very simplified, rather than sophisticated design, including spherical and modular optics, and a fixed elevation. The design was based on the similarly cheap Hobby-Eberly telescope. (Elvis, 2013)

An alternative to building an entirely new facility, would be the acquisition and re-purposing of an older one. This could be both faster, and by far cheaper, especially since the funding for new telescopes has decreased significantly within the past years. For example, the United Kingdom Infrared Telescope (UKIT) on

Mauna Kea, Hawaii, was up for sale in 2012, with the prospection of being closed-down in the end of 2013. (Elvis, 2013) However, since there were no offers from the private sector, the ownership of the telescope was transferred to the University of Hawaii in 2014. Similarly, the National Science Foundation recommended in a review of 2012, that it best divest itself from several large aperture optical-NIR telescopes, and even two radio telescopes. (Elvis, 2013)

However, as discussed in the previous sections remote characterization would best be conducted by space-borne telescopes. The main limitations in this case are as mentioned solely of financial nature, trying to get an adequately sized mirror for a reasonable price, and then launching it into space. The thermal infrared Spritzer Space Telescope for example, has a 0.85m primary mirror, and as one of NASAs Great Observatories, cost some 720 million US$. The optical Kepler mission is equipped with a 0.5m mirror and cost 500 million US$ including three and a half years of operation. WISE cost some 320 million US$. (Elvis, 2013) A single mission of such a scale would most likely solve the remote characterization problem for good. If we would start right now, the entire remote characterization of 20,000 NEOs $> 100m$ could essentially be done within the decade. The fastest approach would be to acquire a large telescope going out of regular operation, and re-purpose it to a NEO characterization facility. The rate of characterization could already be increased to almost 1000 per year with the extra ∼200 NEO observation nights every year. Building an entirely new spectrograph based on a pre-existing design would approximately take about 3-4 years, designing a new one even considerably longer. The construction of a new facility based on the design of SALT would take about 4 years, and would require a site allowing for such a large telescope. However, once operational, it could gather NEO spectra at around 2.5 times the rate of the smaller UKIT class telescopes, which would then easily provide the sought 2000 NEOs characterization per year. (Elvis, 2013) A new explorer-class space mission would also take at least 5 years from approval to actual launch. B612 is trying to reduce the building time down to 3 years. (Elvis, 2013)

After the remote characterization of at least a part of the NEOs, local analysis could begin in bulk. Beginning early with a test program sending out some small probes to analyze some of the currently most promising candidates could help generating know-how on how to best implement a fully optimized mission for the bulk characterization phase. This could enable us to scale up rapidly. Both Planetary resources, and Deep Space Industries count on this approach, planning with a 3-years building time before launch. Unfortunately, the Arkyd 100 series will not be able to operate on interplanetary scale. Still, a first local analysis phase of promising targets could potentially begin within the twenties, with the first results being available within a decade later. (Elvis, 2013)

Some of the programs outlined before have more an industrial than scientific character, as astrophysical and astronomical research does not really require the bulk characterization of NEO orbits and composition. Still, the characterization of asteroidal composition is nowhere near settled science, neither remotely, nor by meteorites, and not even in situ. Most of what we know by now is still rather speculative. One example is the theory about planetesimal formation and evolution, including differentiation, which will need further development before being able to act as guidance in questions of asteroid prospection. Still, the only way to further develop a theory, is to underline it with both, observational and experimental data. The direct linkage between meteoritic classes and the spectral taxonomy of their parent body asteroids is just one example. This implies that even ongoing industrial asteroid mining will always need academic research to further the optimization of commercial prospecting and mining ventures. (Elvis, 2013)

The motivation for academic research like astronomical observations however, are not too effectively motivated by profits or such. Astronomers themselves see only little urge to characterize and analyze great amounts of NEOs in bulk, let alone the entire NEO population. Yet there is good reasoning indicating that science could profit a lot from more detailed knowledge about the inner solar system. The entire situation asteroid miners, and asteroid scientists are in can be compared to the challenges the first major astronomical surveys initially faced. Only few astronomers realized how much influence the acquisition of big data could have on each of their specific fields of operation. Yet the entire astronomy was influenced, by bulk data obtained by surveys like the Sloan Digital Sky Survey. (Madrid and Macchetto, 2009; Elvis, 2013) It is not hard to imagine how bulk data about asteroids could change the view we have on our own solar system. Although the motivation for the George E. Brown Congressional mandate to find 90% NEOs $> 140m$ was more due to planetary protection reasons, than scientifically motivated, is has still revitalized the entire field of asteroid astronomy. Another explosion of scientific data about asteroids may very well lead to a clarifying of the view we have on the processes, which formed the solar system as it is today. (Elvis, 2013)

One way or another, both science and asteroid mining industry would greatly profit on working together on the task of mapping out the inner solar system.

7.3 General ways of mining asteroids

Once the optimal targets are identified and the necessary data required for any mining venture has been acquired, potential miners have to worry about the way they want to exploit the asteroid. As on Earth, where both surficial and underground mining are possible, there are several different basic ways to extract resources from asteroids. All of them have arguments for and against them, and the decision which one to use must be made individually for every asteroid, as the different properties of each object will make some options more or less viable. The size, mass, rotation period, accuracy of the determination of chemical composition, internal structure, orbit, density, and material strength of the asteroid, as well as technological, legal, and financial situation of the company conducting the mining operation, all have strong influence on the various ways to bring the asteroidal resources back to Earth. Mainly, there are four different options on how to retrieve the sought for resources from asteroids, and get them on the stock market back on Earth. The asteroid can be mined in situ, either raw, or with full processing of the materials, the entire asteroid can be brought back to Earth or Lunar orbit, or it can simply be crashed on one of their surfaces. The latter is naturally only a possibility which will most likely be forbidden for Earth, as too many lives are at stake for every single asteroid.

Since neither science nor technology are even close to make asteroid mining possible, all of these approaches remain highly speculative at best, thus a brief review will be given on each.

7.3.1 In situ raw exploitation

To mine for the raw material in situ may be one of the least challenging ways to pursue asteroids as mineral source. Thereby a mining robot would be necessary, which could scrape the ore from the asteroid, more or less crumbling down the entire asteroid in the process, sending the gathered material back to Earth for processing whenever the orbital locations of both Earth and asteroid require the least amount of energy for the transfer of the mass.

To sustain the kinetic energy produced by the excavating tools on the surface, the robot would have to be anchored to the NEO surface or subsurface. If the target body is a differentiated asteroid consisting of rigid, competent and strongly bonded matrices with the material strength necessary to withstand the required amount of kinetic energy, anchors could be set, or simply clamped against the opposing surface. If the target is however to be considered a loose rubble pile with low strength, or even unconsolidated surface material, anchoring may pose more of a challenge. This would require the net forces produced by extraction techniques to be spread over a wide area footprint, analogue to snow shoes on Earth. One such a wide area 'anchor' may be some kind of net, or membrane being wrapped around the surface opposing the mining site, or even entirely covering its surface. Overall there are several possibilities to secure machinery on an asteroid, which mostly depend on the asteroid's properties, and the recoil that the anchor has to withstand. While a net for example would most likely sustain less hold to the machinery, the recoil produced by the mining machinery can be considered to be by far lower on a loose rubble pile than on a differentiated asteroid. This is because the material needs only be scraped up for example with a bucket wheel, as will be reviewed in the next section. One possibility is to tie the spacecraft down with a rope around the entire body, while passing the NEO. This would however require a rather strong surface material. This could be supported by pitons being driven in the surface, one the spacecraft has landed on the asteroid. (Ross, 2001) Another way would be to fire harpoons or penetrators directly from space into the surface, which could, if the material is mechanically competent enough, resist extraction and allow the spacecraft to pull itself in flight down to the asteroid surface. If the surficial material is not strongly enough consolidated for such methods, it could be possible to screw in large area augers, or srew-plates. This would of course require a surface that is loose, and compressible enough for a screw to penetrate. Especially the plates would be screwed into the surface opposing the actual mining site, to provide maximum hold. (Ross, 2001) A bit more specific in property requirement, and demanding for a higher flexibility in application orientation, would be to simply tie the spacecraft to a large, pre-existing, clast, of strong material like metal, or solid silicate rock, which would not have to make up the entire asteroid, but only need to be big enough to secure the space craft. One of the most simple strategies would be to just have the spacecraft completely burrowing itself in the asteroidal surface, by using contra-rotating screws. (Ross, 2001) While requiring the same material properties as the large area augers, it would also make many mining techniques by far easier to apply, as a sub-surficial position of the mining craft would also diminish many problems considering loose rubble flying around high speed, potentially being lost to space.

After the robot is anchored to the NEO, mining can begin, and the material excavated from the asteroid either by drilling, or scraping will need to be efficiently recovered and contained. This is an important issue, as the escape velocity for small asteroids may be of the order of 20cm/s.

For the in situ raw mining approach, only little information about the structure and physical properties are necessary. Basically, the only details needed are mass, orbit, size, and structure, for the mission to find its target and to choose the proper anchoring method, and knowledge of the material that will be mined, and its expected physical strength, in order to choose the mining machinery accordingly. The proposed tools for each type of material are:

- Loose regolith - scrapers, bucket wheels, etc.

- Competent silicate matrix - blast, drill, or cut
- Silicates and ices/hydrocarbons/other volatiles âĂŞ vaporization or scrapers
- Strong silicates and metals/metal ores - blast, cut and crush
- Pure extensive metals - cut

(Ross, 2001)

As long as the excavation tools are chosen according to the expected maximum material strength that is to be encountered, most of the asteroid can be mined. Since no further refinery is necessary, as the entire mined material will be sent to Earth anyways, this limits the count of robotic components susceptible to failure. Any kind of failure once the mission is on the way, will most likely end in the failure of that endeavor, as there is no possibility whatsoever to repair a fully automatic device in mid space due to the large distances covered, and even if the problem was hypothetically solvable, the robot is beyond reach from mission control. Should the mission fail for one reason or another, potentially millions of dollars have gone down the drain, as anything that is lost in space will most likely stay lost for eternity. Murphy's law says that anything that can go wrong, will eventually go wrong, thus the limitation of components susceptible to possible errors is very important. Additionally, this makes the development of a mining device by far easier, and therefore cheaper, as only a few components have to be designed, built and launched, making it one of the cheaper possible approaches to asteroid mining.

The downside of in situ raw mining is the extreme amount of mass, especially of the worthless material, that gets shipped back to Earth necessarily alongside with the valuable resources acquired. This results in extreme amounts of energy required for transportation. If there is no way to gather the fuel for the transportation back to Earth in situ, all of it will have to be stored as part of the mission aboard the robot, significantly increasing its weight according to the rocket equation, and therefore the cost of the mission.

Therefore, this approach can in some cases be extremely cost efficient, for example if some kind of C-complex is the target, where large amounts of fuel can be produced by vaporization of ice, followed by electrolysis, splitting up the water vapor into hydrogen and oxygen. Otherwise however, the concentration of valuable resources would have to be extremely high to limit the useless weight that necessarily has to be carried back to Earth, to justify the transportation of such huge amounts of fuel across the solar system to an asteroid.

7.3.2 In situ full exploitation

In contrast to the raw mining previously reviewed, the full exploitation does not send any kind of low-grade ore, or regolith back to Earth, but only the pure resources that are in demand. For example, rare Earth elements would not be sent on their way contained in banaestite or another mineral, but only as the refined more-or-less end-product, ready for use.

The exploitation of an asteroid in situ, with full refining of the materials gathered following the mining itself, the mass that has to be brought back to Earth can be decreased significantly, compared to the in situ raw mining. Limiting the energy requirements for transportation by reducing mass is one of the easiest ways to increase cost efficiency, and therefore to make operations more profitable. However, this comes at great cost, as this generates the need to fully explore an asteroid before the company can even start to design the mining vehicle. As every little compositional detail can make an entire process impossible on the asteroid, there is no unnecessary information about the object's properties. This would most likely make the use of a lander during the exploration survey necessary to obtain the additional information necessary. While for the in situ raw mining approach, knowledge of the surficial material composition should suffice, as long as minor discrepancies between the asteroid's surface and its interior are calculated (the only requirement there, is a matching material strength), there is a whole new set of parameters considering chemical composition for the processing of the material in situ. This would lead to the requirement of space probe designs different to those currently envisaged by Deep Space Industries, or Planetary Resources.

The main problem however, is the susceptibility of the entire set of mining and processing machinery to errors and failure. Any additional tool sent on its way, needs the means to work for years to come without major problems. This requires an enormous amount of logistic capability to calculate for years in advance. Additionally, any kind of excavation and processing device would have to be more-or-less designed individually for every single asteroid, as every asteroid can be expected to have unique properties and composition, resulting in extreme cost in both development, and construction.

Still, there are several ways already in discussion which may enable the direct extraction of mostly valuable material in situ without having to deal with absurd amounts of refinery. These however would even theoretically work under very specific conditions and further only allow for certain materials to be acquired. The first one was originally proposed by Kuck (1995) and is an analogue to the Fratsch process for the melting and later extraction of the then liquid sulphur, or the solution mining for uranium ore bodies, and salt deposits on Earth. (Kuck, 1995) The process proposed by Kuck would use injected steam to create a circulating solvent inside the asteroid. This solvent would solve certain materials (always depending on solvent, as well as material and material concentration) and therefore enable their extraction by simply extracting the fluid through drillholes and chemically precipitation of the materials to be gained. The benefits are clear, as this would allow for the simple and well targeted extraction of materials with only small overall equipment mass. The fact that, beside the drilling of holes into the asteroid's uppermost surface almost no kind of grinding, crushing or otherwise highly energy intense processes would be necessary, makes the entire vessel planning by far less complicated. As this process requires only a light drill-rig, a fluid collector bag, some equipment for filtration, pressurization, reheating for the heat transfer fluid, and some storage room for the end-product, there are only a few parts of the machinery directly exposed to physical distress. Therefore, a higher life expectancy for the machinery itself can be assumed, making it a safer investment. (Kuck, 1995; Ross, 2001)

Unfortunately, this approach suffers certain risks as well. As every single, simple error can shut down the entire facility on the asteroid, it is hard to state which ones could potentially be the most hazardous ones, but the most spectacular one would be the possibility of a blowout due to the high subsurface pressure (always in relation to the low asteroid gravity, and possibly low material strengths) required for a functioning circulation. This could go so far as to blow away parts of the surface destroying the entire facility, or only create fissures on the surficial layer, leading to the loss of fluid. Especially the pressurization of larger voids within a dormant comet could conceivably cause the entire body to fracture catastrophically. (Ross, 2001) The loss of fluid is one of the most likely occuring problems to cope with, as the solvent could also seep in large pre-existing voids or fissures within the asteroid's interior. This would make the transportation of additional processing materials necessary to the point where this approach may be not viable anymore. However, any fluid seeping out of the circulation process would not only endanger the mission by fluid depletion, but it could also potentially lead to a loss of circulation by interfering with the equilibrium between pumping and re-pressurization. This approach therefore would require a high certainty about the internal physical structure of the target asteroid, which is nothing the current, or near future state of the art in science could possibly supply asteroid miners with.(Ross, 2001)

Further, the matrix permeability is an important variable that may pose an existential risk on this approach, as it determines how far the fluid circulation can reach into the asteroid's material by seeping into it and solve the elements that the miners are after. Without the necessary permeability, the area of effect for the solution would be extremely decreased, essentially making any kind of fluid mining impossible. The permeability of the entire system does not necessarily stay the same for the entire duration of the mining operation, as the most likely narrow return pathways of the fluid could be clogged, either by fine grained solids, such as sediments, clays, and waxes, or by the precipitation of reactant products by sulphur, or hydrocarbons. (Ross, 2001) This could either decrease the efficiency of the fluid mining by creating choke-point in the circulation, or put it to a halt entirely, both of which would have an extremely negative effect on the profitability of the venture. Another problem regards the inefficiency of separation of solids from the return fluid. This could significantly increase the duration of mining activity necessary. This is especially grave considering the strictly limited duration of possible mining seasons and the scarce availability of minimum transfer energy requirement points on the asteroid orbits. (Ross, 2001) The factor most severely limiting the applicability of the Kuck process on asteroids is the essential necessity for the presence of substantial deposits of volatiles in the subsurface, as the uppermost surface itself should not be affected to much by the process as it otherwise would simply dissolve, taking away the protective layer that enables the process in the first hand. Deposits of volatiles worthy of exploitation may include some sort of permafrost, or even massive ice shields.

Another proposed method would be the regolith devolatilization process. This would require a more complex plant to extract materials from the regolith than the Kuck process, as it requires an actual mining facility and must be designed to handle a five times higher mass throughput. This is because the Kuck process requires a target with an ice component of not less than 30% in order to work properly, as it can be expected in the matrix of a dormant comet. The regolith devolatilization process on the other hand, would recover water from hydrated soil minerals where the fraction of recoverable water cannot be assumed to be higher than about 10%. (Ross, 2001) After being anchored to the asteroid, the mining facility would start to excavate large quantities of regolith, grinding it down in the process. The finer grained regolith would then be heated up leading to a depletion in water, which can be collected and stored in the spacecraft. The equipment will therefore comprise of a collector, soil pressurizer, grinding mill with a heater powerfull enough to reach the temperatures necessary, solid-vapor separator, collector and storage bags, tailings, disposal, and a gas cleaning filter, a re-heater and a re-pressurizer. (Ross, 2001) The processing facility itself would not work too differently from those on Earth, allowing for an assumption of throughput rate that is quite similar. A review of the mass throughput rates of comparably simple industrial solids handling systems and pneumatic heating or drying equipment suggests that mass throughput ratios, which is the throughput of kilograms, per day, per kilogram of equipment mass, of 200 or more could very well be possible. This means that a single mining facility of about 5 tons overall weight could pro-

cess up to 1000 tons of asteroid regolith material every day, producing 100 tons of volatiles, resulting in over 10,000 tons of volatiles within a mining season lasting for three months. (Ross, 2001) This process would require a stronger power source than the Kuck process, as additionally to heating, the material needs to be grinded down using kinetic energy, resulting in an overall higher power consumption. The source would most likely be either solar photovoltaic, with a fraction of direct solar thermal energy. The thermal energy could be used to heat the material up, rationalizing away the oven, if the material would instead be just put through some kind of pipe that is painted in black on the outside to heat up to high enough temperatures for the water to leave the regolith. This of course depends mostly on the orbital distance of the NEO to the sun.
As can be seen, the only materials that could be separated and refined in-situ so far are volatiles. This is because Metals, and REEs are already hard to refine and require extremely complex processes on Earth. This would make it that much harder to perform in outer space, under almost zero gravity conditions, with extreme differences in temperature depending on the asteroid's day/night cycle, and everything has to be fully automated to the point, where it can run four years without any failure or error whatsoever. Therefore, this approach may have to be postponed until more sufficient technologies have been developed allowing for a more flexible technical realization.

7.3.3 Asteroid transportation to Earth orbit

The main problem regarding the previously explained in situ mining approaches is the inability to perform any kind of basic repair on the asteroid due to the long distances and the resulting high reaction times. The logistics of such an in situ mining operation would already require the stationing of some kind of repairing device on the asteroids to deal with smaller problems, however larger errors, or something that the onboard robots could not cope with, still demand a reaction from Earth. Considering the time scales on which the mining devices need to operate due to both, their limited energy (as they mostly have to work with solar panels) and the sheer amount of material that has to be processed, it is highly unlikely that a single operation could last for the entire duration without encountering possibly fatal problems sooner or later. Such a problem like the loss of fluid in the Kuck process would require the immediate response from Earth, in order to get the facility operational again. If the asteroid is a travel distance of only one year away when some kind of fatal error occurs, this is the minimum time that the entire facility would not be operational until a repairing robot could reach it. This timeframe requires that the error has already been identified, and a solution can be done remotely, or preferably fully automatic when regarding the long time that any kind of signal would take to reach the reparation robot. Considering the micro gravity on such an asteroid, and the complexity of the machinery present, it is unlikely that any kind of robot could deal with the problems at hand, which would make the presence of a human service crew necessary. This is however highly unlikely, as it may be quite hard to find and employ any service personal that is willing to travel across the solar system for one year to reach an asteroid, only to unclog a pipe that a robot could not reach. Counting in the long list of failed isolation experiments which almost never lasted any longer than a couple of weeks before severe mental abnormalities set in, as the brain starts to make up cognitive incentives if it lacks them naturally, which would most likely be the case if one person was sent on such a journey alone. The time until such mental health problems set in may be longer if the service personal was able to communicate with other people on Earth, however direct contact to other people seems necessary for a person to function properly. (BBC, 2014) One isolation experiment trying to simulate a one year journey to Mars was successful, and six people were able to stay in a building with only 11 meters in diameter for twelve months without any major complications. (FAZ, 2016) If however for every single technical error of the machinery, a six people service crew would have to be sent across the entire solar system in a 11 meter diameter spacecraft, asteroid mining operations would hardly remain profitable. Additionally, the journey over such long distances in outer space would have severe implications for any people's physical health, as they are exposed to the extreme radiative environment of the inner solar system for the entire duration.

Since the development of any machinery for the mining and/or refining of asteroidal material, that can perform for years in a row without any error halting the entire process, and that even without service, or maintenance, is probably a couple of decades away, another approach seems preferably to that in situ.

If we cannot bring the service personal to the machinery on the asteroids, we necessarily have to bring the asteroids and machinery to a distance to Earth on which the crews could operate. The idea is to move a target asteroid into an Earth orbit where it can be mined safely by a mining station that is either directly manned, or where a couple of asteroids are simultaneously mined by automatic machinery under the control of a service crew that can act fast once problems are encountered. To sustain orbital stability long enough for the asteroids to be mined completely, either an orbit beyond that of the moon, or a libration orbit somewhere around the Earth-Moon Lagrangian points L4 or L5 would have to be chosen. (Grandl and Bazso, 2013) As the exact time parameters for the duration of such a mission are extremely dependent on both, the orbital characteristics of the target asteroid, and its mass, it can only be roughly estimated how long it would take to change the orbit of a NEO to be caught in a terrestrial orbit. Grandl and Baszo (2013) estimated it to be between 10 and 20 years, providing that the propulsion system used is technically feasible for such a mission.(Grandl and Bazso, 2013)

The idea is simple, but to actually move an asteroid from a solar orbit to an Earth orbit is an extremely difficult process, that requires enormous amounts of energy, and propulsion systems that are capable of generating the required acceleration, preferably without losing too much mass in the process. Just putting some kind of rocket engine on the asteroid's rear side and push it forward is however not enough, and the modification of a NEO's orbit, to eventually lead to the capture in an Earth orbit requires complicated orbital maneuvers, and extremely precise timing and energy output.

There are several transfer mechanisms available for such a mission.

7.3.3.1 Hohmann transfer

The Hohmann transfer is considered to be the easiest to apply transfer model to change the orbit of an object. Assuming an asteroid with a circular orbit, where the centrifugal force by the kinetic energy of the asteroid is equal to the gravitational force of the central body, a simple Hohmann transfer could be used to modify the orbit to meet the requirements of asteroid miner, by simply changing the asteroids velocity. At first, the velocity would be changed so that the object 'jumps' on a transfer orbit, delivering it to the final orbit, and then the velocity would be changed a second time to move the object off the transfer orbit and onto the destination orbit. The minimum energy would be required if the entire velocity change could be applied instantaneously by some kind of engine burst. This would require a propulsion system that can deliver extremely high peak performance, such as thrusters. If the energy on the other hand would be applied gradually, by a series of carefully planned and executed thrusts to reach an approximation of a Hohmann transfer orbit, this would enable a more efficient operation, as it allows for more flexible reactions on potential mistakes that were made during the planning phase. However, the required change in velocity would be up to 141% higher than with the thruster approach, and the duration of the mission would therefore take that much longer. Unfortunately, the assumption of circular orbits is usually not met, as most NEOs have too high eccentricities. Therefore, a Hohmann transfer would only be possible in the minority of all cases. (Hohmann, 1994; Grandl and Bazso, 2013)

7.3.3.2 Bi-elliptic transfer

The bi-elliptic transfer model is applicable to those NEOs that have not a circular, but an elliptical orbit. It requires not one, but two elliptic transfer orbits, with only one half of each being needed. Therefore the velocity of the target NEO would have to be adjusted three times. The first time to leave its original orbit onto the first transfer orbit, the second time to get from the first transfer orbit to the second one, and a third time to get from the transfer- to the desired destination orbit. While a bi-elliptic transfer requires one additional burst of velocity change compared to the Hohmann transfer model, and usually more time to perform, the overall energy consumption can actually be lower, as long as the ratio of final to original orbital semi major axis is 11.94 or greater. Unfortunately, such large differences in semi major axes is rather unlikely when trying to access NEOs, which are probably the first objects to target for asteroid miners. (Chobotov, 2002; Grandl and Bazso, 2013)

7.3.3.3 Changing the orbital plane

For some NEOs, a change in orbital planes may be necessary due to their high inclinations relative to that of Earth's orbital plane. With a high difference in inclinations, a NEO could not be inserted into an Earth orbit, even if the semi major axis would be fitting. Before that could be successfully accomplished, the inclination of the NEO would have to be decreased. Preferably, the changes of trajectory should be applied when the current asteroid velocity is lowest, meaning when the object is at its apocenter, the most distant orbital point. (Grandl and Bazso, 2013)

7.3.3.4 Swing-by maneuver

Planetary flybys are not only an opportunity to gather data and acquire pictures, but can also allow space probes and spacecraft to gain or lose extra speed. The physical principles behind the swing-by maneuver (also called gravitational sling-shot or break) are nothing else than the conservation of momentum and energy. The flyby thereby transfers a small fraction of the planetary momentum to the spacecraft, which is accelerated while the planet is decelerated. Depending on the geometry of the encounter, the spacecraft can also get decelerated, which in turn would transfer its momentum to the planet leading to its acceleration. (Grandl and Bazso, 2013) The Galileo and Cassini missions have already demonstrated that such an acceleration or deceleration (depending on the stage of the mission) of the spacecraft can save a considerable amount of fuel. It has therefore been proposed by Grandl and Baszo (2013), that the orbit of a NEO could be modified in a way that leads to a close encounter with the Moon. The resulting gravitational deceleration could be used to put the NEO into an Earth orbit without having to burn the large amounts of fuel which would usually be necessary in a bi-elliptic transfer to bring the object into its destination orbit. The Mass ratio between the Moon and any NEO, that could realistically be brought to Earth orbit, is about of the order of 10^{-12}, which means that no negative effects on the dynamic stability due to its change in momentum have to be expected(Grandl and Bazso, 2013).

To bring the asteroids that are targets for mining operations into an Earth orbit has many advantages beside the maintenance of the mining machinery. It would allow us to examine the asteroids more closely, than any pre-designed space probe ever could. The small distance to Earth would further allow us to react more rapidly on small anomalies to investigate them. It would therefore turn potential mining complications into scientifically interesting phenomena or singularities, which could be investigated to further expand our knowledge about the evolution of the solar systems, instead of ruining a multi-billion dollar mission to acquire precious minerals. The orbit modification itself would most likely require only the most basic data such as information about the mass and orbit, and depending on the propulsion system of choice maybe the surficial material parameters like material strength, in addition to any data necessary to decide whether it is a potentially lucrative target in the first place. This means that the swarm of space probes that would have to be sent out to investigate the NEOs on their original orbits, would have to acquire by far less data than required for the in situ mining approaches, as the targets can still be investigated on their structural properties and exact compositions once they are in the Earth orbit. This would make it feasible to design only one large type of prospection spacecraft that would never leave the Earth orbit, but instead just probe every single asteroid that is delivered directly to it. Since this approach would require only a few of these prospection probes, they could be equipped with the most sophisticated tools available, without costing as much as if they were required to do swarm in situ investigations. These survey probes could supply us, thanks to the better equipment, with more information of higher quality and would therefore allow the construction of a better mining device, specifically designed to cope with the investigated environmental conditions at hand. The more we know about the asteroid, the better we can prepare any mining device for the specific situation on the asteroid, which would in turn lead to a mining process with fewer complications than any in situ mining mission ever would.

Unfortunately, the huge masses that would have to be transferred to Earth orbit pose an obstacle to the realization by using conventional propulsion systems. Thus, there is a demand for new, advanced propulsion systems that are able to provide high thrust, and a specific impulse. One such future propulsion systems may be the Bussard Fusion System, the so-called quiet-electric-discharge (QED) engine. (Grandl and Bazso, 2013; Bussard and Bussard, 1997; Bussard Ph. D, 2002) It consists of electrostatic fusion devices to fuse Deuterium and Helium-3 to Helium-4+ protons, releasing 18.3 MeV energy per reaction. The charged He-4 protons can then either be used to generate electrical power, or to directly generating thrust by using them as a plasma beam. This system is advantageous compared to the Deuterium-Deuterium fusion, as it releases fewer protons, which both attack the reactor confinements, and are unavailable for the generation of thrust. The only disadvantage being the low fraction of He-3 on Earth, making it a scarce resource until the presumably rather vast lunar deposits are exploited for consumption. For this reaction, a specific energy of $3.5 * 10^{-14}$ J/kg can be computed, making it orders of magnitude more potent, than any currently existing propulsion system. (Grandl and Bazso, 2013; Bussard and Bussard, 1997; Bussard Ph. D, 2002)

The other problem with the approach of transferring the NEOs to Earth orbit, is that terrible accidents and miscalculations could happen. A direct collision of an asteroid on its way to an Earth orbit with our planet would be rather unlikely, yet nothing should be ruled out. It has been argued by some, that a maximum diameter of 20m for every asteroid, that is to be brought to Earth orbit, should suffice, as any asteroid below that size would mostly disintegrate on an accidental journey through Earth's atmosphere. (Sommariva, 2015) While this coincidentally is the same size as we would be able to transfer in orbits, it has been argued by some (Grandl and Bazso, 2013) that a size of more than 100-150m would be necessary, to be a lucrative target for orbit modification followed by exploitation.

Hypothetically, this approach is applicable to all kinds of asteroids, but the higher the material strength and the stronger the structural integrity of the body are, the better the modification of its velocity works. This would make it extremely hard for asteroid miners to apply this approach to loose rubble pile NEOs, which are only held together gravitationally, since quite a fraction of the kinetic energy delivered by the propulsion system may be transferred into the asteroid interior where it is transformed into thermal energy by friction between the different grains and rocks. Therefore another approach would have to be found for this kind of asteroid, unless a solution to this problem is found, for example by sealing it at least at the surface to create some surficial stability strong enough to withstand the force of the propulsion systems.

7.3.4 Asteroid impact on Moon or Earth

The last, and potentially most unlikely way to mine asteroids is to bring the target NEO near to Earth, but not to place it in an at least temporarily stable orbit, but to actually crash it onto the surface of either Earth, or the moon. While this can be extremely risky, especially if crashed on Earth, there is currently no law forbidding it, and scientifically speaking, it is still an option and will therefore briefly be reviewed. While the transfer of an asteroid to near Earth orbit itself can already be deemed potentially hazardous, a direct crash with Earth would require a significant error in one of the key components measured, as the target orbit would most likely be somewhere near the Earth-Moon Lagrangian points, or an orbit even outside that of the Moon. These extremely large distances give plenty of space for smaller assumption or calculation errors. If however, Earth's surface is the target of the asteroid, smaller miscalculations can already make the difference between hitting in the middle of the Sahara, and downtown Rome. If this approach should still be chosen, it would make sense to choose a large, preferably unpopulated area as target. Since the asteroid would later have to be recovered, it further must be an easily accessible area, disabling any kind of jungle, ocean, swamp, or mountainous area, leaving either deserts, or savanna as landing site. The target asteroids would have to be specifically chosen to both, withstand the extreme conditions a touch-down on Earth would provide, and contain resources that are actually worth transporting to the terrestrial surface, instead of being only really lucrative in space (like water as fuel). As especially small asteroids would potentially fully disintegrate on their journey through Earth's atmosphere, sufficiently large asteroids are necessary for a financially lucrative fraction of its mass reaching the surface to be mined. Further, an asteroid should be chosen that could structurally withstand the extreme forces that work during interaction with the surface. Should the asteroid fracture in the higher areas of the surface, it could lay a devastating hail of meteorites on a large area. Additionally, this would lead to a larger surface/volume ratio, resulting in a higher mass loss due to vaporization during its flight, significantly decreasing its potential value. These considerations would make high-PGM-content M-type asteroids the logical targets for such an approach. Their high iron and nickel content would make them rather resistant to fracturing during flight, and the PGM-concentration would make them very lucrative targets to exploit on Earth.

Another problem may be the legal situation at hand at the landing site. Considering that a high precision landing can almost naturally ruled out when it comes to irregularly shaped objects crossing through Earth's atmosphere, the location of the landing site could vary between several different countries, which all have different laws on the property rights of 'natural' resources. As the entire legal situation of asteroid mining currently is debatable, this would most definitely be the approach where troubles with national laws seem immanent, and a quick solution regarding the legal administration of such ventures seems necessary.

The advantages of this approach lay clearly in the simplicity of the actual mining operation. While all the other approaches have to deal with space environment, micro-gravitation and high transport and maintenance cost during the entire process, this way is should less be considered 'asteroid mining' but more a terrestrial mining of asteroid resources. It would make the development and launch of any mining robots unnecessary, as the entire resources can be gathered the conventional way after the asteroid has 'landed'. This would further make the exploitation of the asteroid resources that landed by far more efficient than it could ever be in space. Further, this approach would reduce the amount of velocity changes for any kind of orbital modification by one, as there is no necessity for the last velocity change to put the object into the destination orbit, since any excess velocity would only produce additional thermal energy during impact. This would therefore reduce the mission cost by decreasing the amount of fuel that has to be transported to the asteroid. A careful mission plan could also use swing-by maneuvers around the Earth or the Moon to decrease the kinetic energy of the NEO to further limit the impact energy.

Considering the large amounts of collateral damage and civilian casualties that may be inflicted by deliberately crashing an asteroid of potentially hazardous size on Earth, it can be assumed that there would laws created forbidding it, as soon as a corporation announced its plan to do so. Additionally, such a venture would probably be a public relation disaster for everybody involved. However, the surface of the Moon could still be a target for resource mining by asteroid impact. The absence of any population and lack of both flora and fauna makes this approach ethically more sustainable than a deliberate impact on Earth. Further, the lack of an atmosphere would result in a lower loss of material due to vaporization, however depending on the size of the target asteroid, the kinetic energy during the impact could accelerate considerable amounts of mass over the escape velocity, essentially losing it to space.

Since there is no need for any resources mined from asteroids on the moon yet, any material mined there would still have to be brought either to Earth or to its orbit, costing additional fuel for the transport. The only real reason why this approach could be chosen is either the development of a lunar industry which would create a demand for raw material up there, or if for some reason or another, the mining of asteroids in low to zero gravity environments should prove to be impossible.

7.4 Scientific strategies

As we are technologically, and scientifically still some years away from actually being able to mine asteroids, there are no definite answers yet of how to overcome the obstacles described in the previous sections, or which way of mining and transportation will eventually turn out to be the best choice. However, both scientists and future asteroid miners are working hard on finding ways to cope with the problems lying ahead of us. Over the years, many have proposed creative and inventive solutions, which are often not only applicable to asteroid mining ventures but could end up revolutionizing the exploration of space as our new frontier. Some of the most interesting approaches are described in this section.

7.4.1 Electric-sail

One of the main problems of asteroid mining that increases the price for any potential operations is the extreme amount of fuel that is necessary to either directly modify the orbit of an asteroid, or to retrieve the materials mined in situ by. According to the rocket equation $\Delta u = V_{eq} * ln(\frac{m_f}{m_e}$ (where Δu is the maximum change of velocity of any vehicle, V_{eq} is the effective exhaust velocity, $\frac{m_f}{m_e}$ is the propellant/mass ratio), the fuel tanks required to retrieve any mass from NEO orbits increase the overall mass that has to be launched significantly.(NASA, 2014) Thus, the search for more mass-efficient transport and propulsion systems is a key step towards realizing asteroid mining. One method to limit the fuel requirements for propulsion in outer space is to use the natural energy resources provided by the solar system itself. Some have argued for solar sails, which are proposed to use the kinetic energy exerted by photons on reflecting surfaces. Solar sails have often be brought up as propellant systems for possible future space operations, most recently by the Russian billionaire Juri Milner for the 'seeding' of life as we know it on relatively close Earth-like exoplanets. For his project, Milner envisioned extremely strong Earth or Moon based lasers to speed up microscopically small space probes by directly pointing on their solar sails. Due to the small mass of the crafts, they could reach velocities up to a few percent of the speed of light. (derStandard, 2017)) While this is a possible approach for the fast deliver of small mass spacecrafts across the solar system and even beyond, the use of solar sails for mass transportation in our solar system poses different problems. One of the predominant ones being that the sun seems unwilling to focus enormous amounts of solar energy on the sails of a certain spacecraft, as we would be able to with strong lasers. However, the position of such stationed lasers would mean that we can only use them to bring mass away from the Earth-Moon system. The solar wind however is simply not so strong that relatively small sails would suffice to propel large masses. Even if it were, the thrust produced by photonic solar sails decays with F$\sim 1/r^2$, making it extremely impractical for any journeys that lead to greater solar distances. Additionally, the solar wind sails need to be strong enough to withstand the force of the thrust they produce, thus an extremely strong material would be necessary for the delivery of thousands of kilograms mass of a mining operation facility. Further, solar sails provide energy according to their surface, which means that these sails would have to be extraordinarily large, and therefore withstand extreme forces, in order to transport such spacecrafts. (Janhunen et al., 2015) All of this means that, while being the perfect propulsion system for the fast transportation of small micro probes to other solar systems by direct laser irradiation, the solar sail technology seems insufficient for asteroid mining ventures.

Janhunen et al. (2015) have therefore proposed the use of a different component of the solar wind: the plasma flow. The so called E-sail would use charged tethers to extract momentum from solar wind ions by electrostatic Coulomb interaction with the solar wind's plasma flow to produce thrust. (Janhunen et al., 2015) The available pressure of the plasma is only about 1% of that of solar wind photons, however the E-sail can compensate that lower availability of energy per mÂš simply by scaling up. While the photonic solar sail needs a large closed area for the gerneration of thrust by photon impact, the E-sail works with magnetic fields exerted by the charged tethers. These can be arranged as some kind of net by rotation, which makes the area it can span by orders of magnitude larger than that of a common solar sail. This net approach makes it also considerably less vulnerable to micrometeorite bombardment than a photonic solar sail, as even if one string was severed, the current necessary to provide thrust could still reach almost every part of the sail. This minimizes the mass required to cover a large area of effect. The tethers are charged with a simple electron gun. The energy required, to charge the tethers would be provided by small photovoltaic panels, which means that this would be a propulsion system that does not consume any kind of fuel. (Janhunen, 2004; Janhunen et al., 2010) According to current estimates the E-sail is about 2−3 orders of magnitude more efficient in terms of produced lifetime-integrated impulse per propulsion system mass than any current propulsion methods like chemical rockets or ion engines, if the mission duration is about 10 years, and the mission does not go out too far into the outer solar system. (Janhunen et al., 2010) This is based on numerical simulations conducted by janhunen (2009). These simulations are in good agreement with laboratory measurements when run for plasma representing LEO conditions. (Janhunen, 2014, 2009; Siguier et al., 2013)

The thrust provided by the E-sail is thereby inversely proportional to the distance of the sun by F∼1/r, which means that it is more fit for use in larger solar distances than the photonic solar sails. The electric power consumption per produced thrust is about 1kW/N at 1 au distance from the sun. (Janhunen et al., 2013) For a fixed tether voltage, the power consumption is directly proportional to te electron current gathered by the tethers' magnetic field, which is proportional to the solar wind density, that decreases by $\sim 1/r^2$. Since the power source for the charging of the tethers is photovoltaic, the energy provided also decreases with $1/r^2$, since the illumination of the panels is too depending on the density of the solar wind. This means that the photovoltaic panels designed to power the tethers at 1 AU distance from the sun, also suffice to power them at any given point in the solar system, assuming a constant efficiency of the photovoltaic power system. Therefore, the E-sail has a good potential for serving as the propulsion system of choice for long-lasting solar system missions. (Toivanen and Janhunen, 2017)

As the thrust is not generated by impact, but by deflection of plasma, it is possible to vector the E-sail thrust in a cone of about 30° around the solar wind velocity vector. (Toivanen and Janhunen, 2012) Therefore, maneuvering and trajectory control are possible, as the gravitation of the sun can be used as a resistance to the radial force, enabling some sort of 'cruising' through the solar system. This means that the E-sail is not only a possible propulsion system to get further out in the solar system, but also to retrieve material from more distant areas, and bring them back to Earth. It is also possible to adjust the magnitude of the produced thrust between 0 and 100%, simply by modification of the current and voltage of the electron gun. Maximization of the available thrust can be achieved by adjusting the electron gun current to the current gathered by the tethers, which leads to a situation where negative feedback mechanisms compensate the variation in solar wind dynamic pressure. (Toivanen and Janhunen, 2009) The maneuverability of E-sails, while being strongly limited by the 30° cone, completely suffice to reach destinations such as Mars, or the asteroid belt.(Janhunen, 2014; Toivanen and Janhunen, 2009; Mengali and Quarta, 2014; Quarta et al., 2014; Quarta and Mengali, 2010) One large E-sail equipped spacecraft could reach the main belt within a year, and bring back up to 3 tonnes of material within only three years, consuming no fuel. (Quarta and Mengali, 2010; Quarta et al., 2014)

Figure 7.1 Shows a schematic depiction of an E-sail.

However, there are still some disadvantages about the E-sail propulsion system. Firstly, the 30° cone, to which propulsion trajectory is limited means that it can not be used as a break. This leads to a situation, where it is extremely cheap to reach a target, but where the spacecraft can't land without crashing, as the travel velocity is the same as the landing velocity. While this can be compensated by using conventional chemical rockets as a break, that still somehow defeats the purpose of reducing the transported mass, especially since the mass of the entire E-sail has to be calculated in for the breaking equation. This means that the entire propulsion system is relatively suboptimal for sending any mining facilities to NEOs. However, it could be used to carry the material gathered by any mining facilities in situ back to Earth, if packages of raw or processed materials are prepared which the E-sail spacecraft can pick up without having to reduce velocity. Later that spacecraft could use a swing-by maneuver with a near planet or moon to turn around and come back towards Earth. Secondly, the E-sail provides thrust over time, which makes it unfit for orbital modification, where very high thrusts have to be provided within very little time. Further, orbit modification involves rotating, spinning and

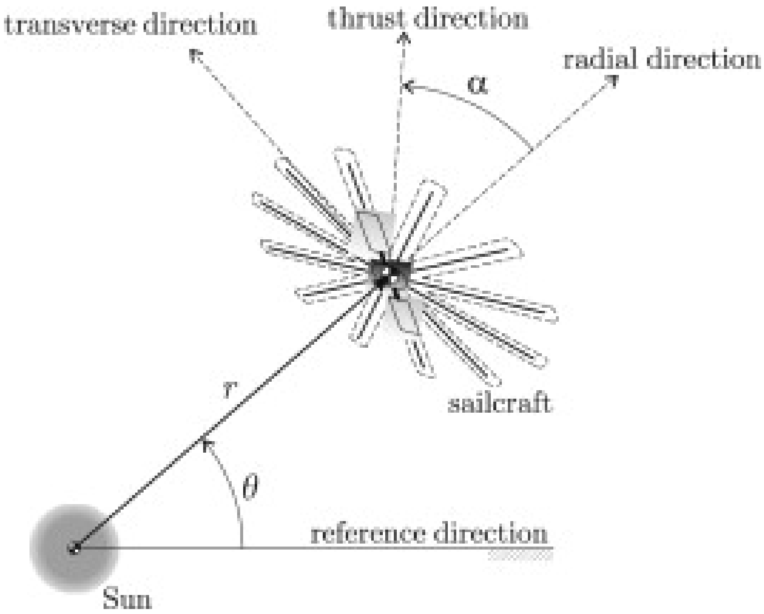

Figure 7.1: A schematic depiction of an E-sail with it's 30° trajectory cone relative to the solar wind trajectory, Credits: (ascelibrary, 2014)

tumbling asteroids, where the direction in which the E-sail is projected, steadily varies. While being limited to only certain aspects of asteroid mining, the E-sail can still be considered a critical enabling technology, which may be necessary for making asteroid mining operations economically feasible.

7.4.2 Space tugs

Orbital modification of an asteroid is no easy task and it would require not only exact knowledge of the dynamical behavior of an object and its exact mass, but also a propulsion system fit for such an endeavor. Such a propulsion system would need to supply high impulse thrusts within very short timescales for the bi-elliptic transfer to work, as well as a geometry, which is suitable to control the direction of the thrust for navigation. As it can be assumed that the entire spacecraft sent to the NEO to bring it to Earth orbit will have no other purpose than that, it would most likely consist of not much more that the propulsion system itself, the fuel tank, and an anchoring system to secure it on the NEO. As any additional equipment for the production of additional fuel in situ would only make the concept that much more liable to errors, all of the fuel required for the orbital maneuvers would have to be brought to the asteroid well stored within fuel tanks on the spacecraft. Therefore, a reaction that requires the minimum mass for the production of the necessary energy should be used to decrease the mission cost as much as possible. Considering the long mission duration for every single NEO transferred to Earth orbit, a parallel approach seems logical to reduce the otherwise probably quite large downtimes for any mining machinery waiting in Earth orbit. Therefore, a design somewhat suitable for mass-production should be optimal.

Grandl and Baszo (2013) have proposed a concept called asteroid space tugs to be used for the transport of asteroids to Earth orbit. These space tugs would use the proposed Bussard Fusion System to create the necessary high thrust. Considering the high energy-yield of the Deuterium-Helium3 reaction of about $3.5 * 10^{14}$J/kg, it can be assumed that such an engine would be one of the most mass-efficient propulsion system in terms of fuel.(Grandl and Bazso, 2013; Bussard Ph. D, 2002; Bussard and Bussard, 1997)

As an example application they calculated the energy and fuel requirement necessary for the transfer of the asteroid 2008 EV5 to Earth orbit. The Aten asteroid has a mean diameter of about 450 meters, and is classified as a taxonomic S-type. Assuming a bulk density of about 3g/cm^3, its estimated mass is about $1.4 * 10^{11}$kg. Currently, 2008 EV5 has an aphelion distance of about 1.038 AU, and a Δv of about 5.5km/s. They therefore calculated the specific energy necessary to bring it to an Earth orbit to be of the order of $2.4 * 10^{18}$J. Considering the reaction efficiency of $3.5 * 10^{14}$J/kg, about 8,000kg of fuel would be necessary to transfer the object to Earth orbit. By applying the thrust of the propulsion system, the object's velocity is increased just enough so that the line-of-nodes is oriented parallel to that of Earth. With 2008EV5's current Aphelion distance, this would allow for a close encounter with the Earth-Moon system when crossing the nodes. If the orbit modification is planned and conducted in such a way, that the asteroid is still in safe distance to Earth, but close enough to the Moon for a swing-by maneuver, the remaining δv can be supplied by the Moon. (Grandl and Bazso, 2013)

Since series production would significantly reduce the production cost in the long term, they proposed for the space tug parts to be modular, which would allow for a more flexible assembly of the final propulsion-spacecraft, which is best suited for the specific requirements of a target asteroid. Additionally, this would allow for a more easy assembly of the spacecraft in low Earth orbit. The structural support would be given by cylindrical modules, made out of aluminum trapezoid sheeting, stringers, frames, and bulkheads. The size of the separate modules would probably be limited to the maximum size the large carrier rockets of the time can transport to LEO. Considering the currently used Ariane 5 rocket, this would be approximately 24 meters in length, and about 8 meters in diameter. (Grandl and Bazso, 2013) Once the modules are brought to LEO, they would be assembled in fours, to form space tugs and sent on their way to the target NEO. Once the space tugs reach the target object, they will deploy their drilling anchors (or other anchoring systems of choice) and fix the tugs to the asteroid's surface. Once the space tugs are fixed, they can apply forces in every direction by firing their engines accordingly. For the hypothetical target 2008 EV5, a total of 8,000 kg of fuel have been calculated, but for safety considerations some additional fuel for adjusting maneuvers after the final swing by should be added. To stabilize the NEO during these additional thrusts, a second space tug is needed to apply counter forces. The primary would thereby apply the greater part of the force for orbital maneuvers and therefore carry most of the fuel, whereas the secondary tug would mostly adjust the flight track by short engine thrusts. The orbit modification mission would either be supervised, or remotely controlled from Earth. To enable communication between the Earth control center and the space tugs, the tugs will be accompanied by small communication satellites orbiting the NEO. (Grandl and Bazso, 2013)

7.4.3 Gas filled enclosure

All currently proposed systems for the capture of asteroids have to disrupt an asteroids surface in order to deliver the necessary propulsion for orbit modification. (Jenniskens et al., 2015) Any kind of spinning or tumbling of the target asteroid on its orbit imposes big problems on the capture and modification of the asteroid's orbit. Also for in situ operations, this could be dangerous, as any in situ mining machinery will most likely rely on the availability of solar irradiation on its solar panels, at least periodically to charge batteries. This would be necessary to ensure power supply when the solar panels are located on the asteroids nocturnal side. With irregular tumbling, the periodic recharging of the batteries would be in danger, which could either lead to down times, when the batteries died, but also severely damage the batteries by irregular charging cycles.

Therefore, the current concepts target asteroids, which are solid large boulders, so that they can easily be transported by conventionally designed propulsion systems such as the previously described space tugs. However if that should be tried with a large rubble pile, the force of an engine thrust would most likely disintegrate the entire asteroid. Even if the rubble pile asteroids would simply be packed into a bag before propulsion, this would firstly require the bag to be strong enough to withstand the forces during propulsion, and secondly not solve the problem with the tumbling. Further, such an approach would destroy the asteroids structure and many primitive and fragile features would be lost for science to explore.

Jenniskens et al. (2015) have therefore presented a concept for a gentle asteroid retrieval with a gas-filled enclosure called SHEPHERD. It could be used to capture and de-spin a rubble pile asteroid of uncertain mass, shape and spin rate. The concept of SHEPHERD is based on creating a sealed enclosure around the asteroid and fill it with up to 0.1 atm of Xe gas. The gas will thereby gently de-tumble and de-spin the asteroid by friction. The SHEPHERD system would include a control computer for navigation and onboard systems, around 10 tonnes of Xe gas, gas pumps, and a solar electric propulsion (SEP) system, and a balloon large enough to fit in the asteroid. The balloon would consist of an outer side facing space, an inner side facing the asteroids. (Jenniskens et al., 2015) SHEPHERD would first rendezvous with the asteroid and perform a 3D LIDAR scan of the asteroid from all sides providing exact shape, center of mass, and spin states. Then it would fully deflate around the asteroid by injecting gas beams between the outer and the inner layer of the balloon by using air beams that support the inner side of the tent to guide it safely around the asteroid. The balloon material would be drawn from storage bays around the perimeter of the SHEPHERD spacecraft. To avoid any stresses, the balloon material will float freely over the airbeams, surrounding the asteroids, to form an open C-shape. During this phase, SHEPHERD would approach as close as 10 m distance to the asteroids principle spin axis, and choose the optimal position for its solar panels and front thrusters. Cameras on the inner balloon would thereby provide positional awareness so the balloon comes no closer than 3m to the asteroids surface, as it could easily damage the balloon material. Once the asteroid is completely surrounded by the balloon and the balloon is fully deflated, the open end of the enclosure would be pulled together, closed and sealed. The closing mechanism are two built in cinch ropes that are pulled by two motor driven rollers, and are attached to the open end of the fabric. After the balloon is sealed, gas would be injected gradually to fill the void between the asteroid and the balloon, acting as a break for the tumbling using turbulent dissipation. (Jenniskens et al., 2015) To minimize the transfer of angular momentum from the asteroid to SHEPHERD, it gradually dissipates energy and angular momentum by heating and shear. If the spinning or tumbling of the asteroid is slow enough, SHEPHERD can entirely compensate this by using solely its own directional thrusters by pointing the gas stream in the opposite direction. (Jenniskens et al., 2015) After reaching the peak pressure of up to 0.1 atm, a pressure of about 10 kPa would be exterted evenly distributed across the asteroids entire surface. The asteroid would most likely not disintegrate due to the friction however, as the ram pressure at the edges of the spinning body would be of the magnitude of 0.05 Pa, whereas the cohesive strength of a weakly consolidated rubble pile asteroid is assumed to be around 25 Pa. (Sánchez and Scheeres, 2014; Jenniskens et al., 2015) After successful de-spinning of the object, it can be brought back to Earth intact, which could provide helpful insights into asteroidal interior structure for science. Further, this approach would make it possible to exploit even heavily spinning asteroids of weak to mediocre consolidation, as a de-tumbling would make it by far easier to retrieve the asteroid. However, not only the orbital modification mining approach could greatly benefit from such a mission, as fast rotation can also endanger any mining equipment located on an asteroidal surface due to additional centrifugal forces, a de-spinning may be necessary for some targets before a mining operation could start.

One of the greatest features about the SHEPHERD concept is the re-usability. The entire process is reversible, and only the sealing of the bag's open end has to be renewed, making it a long-term investment that could revolutionize asteroid science. If anything should fail during a mission, like a loss of Xe, it can still fully inflate, wrap around the asteroid like a bag and try to retrieve it without fully de-spinning it first.

One of the major problems in its applicability however, is the obvious limit in size, as only a limited amount of Xe gas can be stored aboard the module. Further, the higher an asteroid's mass is, the smaller the chance to de-spin it without significant fractions of angular momentum being transferred to SHEPHERD. Still, the gas sealed enclosure is one of the only scientific strategies so far, addressing a potentially major problem to asteroid mining operations: tumbling asteroids.

7.4.4 Bucket wheel

Another big problem considering the mining of asteroids is the extremely low gravity easily leading to lift-off due to excavator thrusting. As many asteroids typically have escape velocities of only a few cm per second, this utterly disables many techniques like the use of explosives, as they create so much kinetic energy, that large amounts of the material will be lost to space. Some scientists have therefore argued for a subsurficial excavation by drilling cavities and tunnels into the asteroids to help keep the excavated material in place. However, this will only work for asteroids where the material and structural strength allow for large fractions of the asteroid to be excavated without the entire object collapsing, potentially destroying the entire facility. If the target asteroid should be a rubble pile however, subsurficial excavation is not a possibility, as the surface would crumble away. Therefore, a way to conduct surface mining is needed where only little kinetic energy is applied, not only to minimize the loss of asteroidal material. Nallapu, Asphaug and Thangavelautham (2017) have proposed the use of bucket-wheels for surface mining of asteroids. (Asphaug et al., 2017) Since any of the excavation mechanisms faces the danger of lifting off the surface on an asteroid if the recoil produced by its own activity imparts the escape velocity, it is extremely important to either give it additional support, or to minimize the kinetic energy applied during the mining process. Especially on rubble pile asteroids, anchoring can be rather tricky, especially if the circumference of the target object is large enough to limit the applicability of nets covering vast parts of the surface area. Thus, a system of counter rotating bucket wheels, like RASSOR developed by NASA KSC could work, as it can apply the necessary vertical plunge force. The counter rotation thereby ensures that the horizontal velocities are not imparted, and the vertical plungers compensate lift-off due to any reactive-excavation forces. (Asphaug et al., 2017; Mueller et al., 2013; Nakamura and Smith, 2011) The excavation tool has been proposed, to be powered with solar insolation. The solar panels thereby would generate power based on the respective current soar irradiation, charging onboard batteries, which could supply energy if the solar panels reside in the nocturnal asteroid site due to its rotation. (Asphaug et al., 2017) The system called In-Situ Ressource Utilization (ISRU) is designed to excavate hydrated minerals within asteroid regolith, extract the water by heating the regolith, and electrolyze hydrogen and oxygen from the water using solar power. Thereby it could sustain itself, as small amounts of the hydrogen and oxygen produced could be used to supply additional power within power cells if necessary. (Asphaug et al., 2017) By exerting a radial thrust, the counter rotating wheels could prevent any lift-off vertical forces, depending on the various magnitudes of forces. The bucket wheel would be an easily automated mechanism, as every force it experiences is a necessary consequence of its own action and can be reduced simply by slowing down the rotation, making it comparably better than any kind of explosives or drills. Drills produce the recoil by having to press harder on the asteroids surface depending on the material strength, and explosives can lead to an unequal force distribution , depending mainly on internal structure. The only problem of the bucket wheels is that they can only work up to a certain material strength, which makes it unsuitable for many desired M-type objects.

7.4.5 Asteroid colony

Due to the technical problems considering the in situ mining of anything else than volatiles like water, this approach can most likely be ruled out for the earliest mining operations. Especially since the orbital modification is not nearly as hard to conduct, and the only real problems being not technical complexity of fully autonomous mining facilities, but only the availability of optimal propulsion systems. As in situ full processing of Platinum group metalss or rare earth elements is even more complex than the raw in situ mining approach, most of the asteroid's material would have to be brought to Earth anyway, so there is not such a great difference in transport weight when the entire asteroid is brought to Earth orbit. However, even if in an Earth orbit, the exploitation of an asteroid is no easy task, as many factors have to be calculated in when outlining the missions. The main advantage of bringing asteroids to Earth orbit before mining it is the accessability for manned missions, which would solve many problems regarding the automatization of machinery. Additionally, the short supply route could help provide existential efficiency to maintenance and repair. However, other problems regarding asteroid mining remain, such as the low gravity at hand, which could easily result in the loss of the entire mining equipment, if not anchored adequately, or the loss of excavated materials if mined directly at the surface, exposed to open space.

Grandl and Bazso (2013) found a way to use the gravtitational disadvantage on asteroids for better exploitation. They proposed to conduct subsurface mining on asteroids, and fully excavate their interior, leaving only the uppermost surficial crust as a protection against the strong radiation and to hinder the excavated mass to fly off into space if propelled beyond escape velocity. The interesting part thereby is, that the remaining asteroid hull can be relatively thin and still remain stable, due to the lack of gravitation. (Grandl and Bazso, 2013) Once only the hollow asteroid remains, it could be used as a supply base for further asteroid mining ventures, or even to store the excavated materials for more favorable orbital conditions for the transport back to Earth, or more favorable prices on Earth's stock markets where the mined resources will eventually be sold to the highest bidder. An alternative that may sound like science fiction for now is that the hollow asteroid could also be used as a base for a human colony in outer space.(Grandl and Bazso, 2013)

Grandl and Baszo (2013) proposed for a manned mining station to dock to the asterid's surface once it has been stabilized in Earth orbit. The station would be built of cylindrical modules and nodes to make in space assembly easier, as the components would most likely have to be brought to at least low Earth orbit separately. A modular design would further allow a more flexible approach, as each mission can be assembled optimized for the various conditions at hand. The design would of course include a drilling machine called 'active mining head', conveying, and processing machinery. (Grandl and Bazso, 2013; Taylor et al., 1995) Linked storage and docking modules would allow carrier spacecrafts to take up gathered materials for transport back to Earth whenever available. For the crew, rotating mining habitats provide a small amount of artificial gravity. The power source of the mining station would be both solar panels, and a small nuclear battery. (Grandl and Bazso, 2013)

The mining itself would be much different than that on Earth. On the one hand, the low gravity would make the drilling and stabilization of tunnels easier, as fewer rings and rock bolts suffice. On the other hand, the low gravity environment makes conveying of the excavated rock particles known as 'muck' more difficult, as mentioned above. As this makes subsurficial mining necessary, this also limits the choice of asteroids suitable for this approach to those with a density of more than 2g/cm^3, since drilling at a lower density could destabilize the structrural integrity of the rock. (Grandl and Bazso, 2013) The active mining head is a flexible machine for drilling, digging, and boring, which is equipped with cutting elements made of artificial diamonds. Due to the low stability of the present rock, this active mining had would have to work slower and more precise than required on Earth. At first, a main tunnel would be drilled, with a diameter of about 8m reaching to the center of the asteroid. Once completed, the main tunnel allows the excavation of up to 50% of the asteroids volume, with the created cavern being filled with pressurized gas. The gas would allow the muck to be conveyed with a simple flexible vacuum conveyor tube. The conveyed material would then be stored in the mining station storage modules, where they can be picked up by unmanned cargo ships for transport to its final destination, which would either be Earth, or some sort of developing space industry. Since the storage on the station is limited, an equilibrium between the excavation and evacuation of material should be found. This equilibrium depends on the availability of energy for the mining head, the structural stability of the asteroid and the availability of cargo ships, but a solution should be found with relative ease considering the proximity to Earth. (Grandl and Bazso, 2013) Due to the lack of water and air in the asteroids interior, the surface of the main tunnel and the resulting cave can't be lined with concrete, as is usually done on Earth, making the stability of the rock a more immanent concern during mining. Once the inner cave is completed and the excavatable material has been evacuated, the cave surface can be sintered with lasers to smoothen the walls. The remaining asteroid crust should be at least 30-50m thick, depending on bulk density, gravity, and diameter of the cave. The hollow asteroid could then be used as a perfect shelter against micometeorite bombardment, irradiation and thermal insulation for industrial facilities capable of complete processing of resources excavated from other asteroids, or even space colonies suitable to sustain human life in space, providing shelter, and even artificial gravity. (Grandl and Bazso, 2013) The development of refineries and heavy industry in outer space would drastically drop the cost of space missions in the long run. If the heaviest components of space missions could be produced in outer space, the main factor of cost, the transportation of mass from Earth to space, would be largely eliminated. Hollow asteroids as a side product of asteroid mining could prove a valuable site for the construction of such heavy industry.

Figure 7.2 Shows a schematic depiction of an asteroid colony.

While the development of a space industry poses both financial, and scientific benefits and opportunities, the colonization of space by humankind has its very own flair, thus Grandl and Bazso (2013) have designed the outline of an asteroid colony. (Grandl and Bazso, 2013) After the excavation of half the asteroid's volume, a rotating toroidal colony could be built in the remaining cavern. The rotation would provide an artificial gravitation that allows long term human presence without suffering the usual health consequences from space trips like disorders in the production of blood, or degeneration of muscles. To minimize the Coriolis

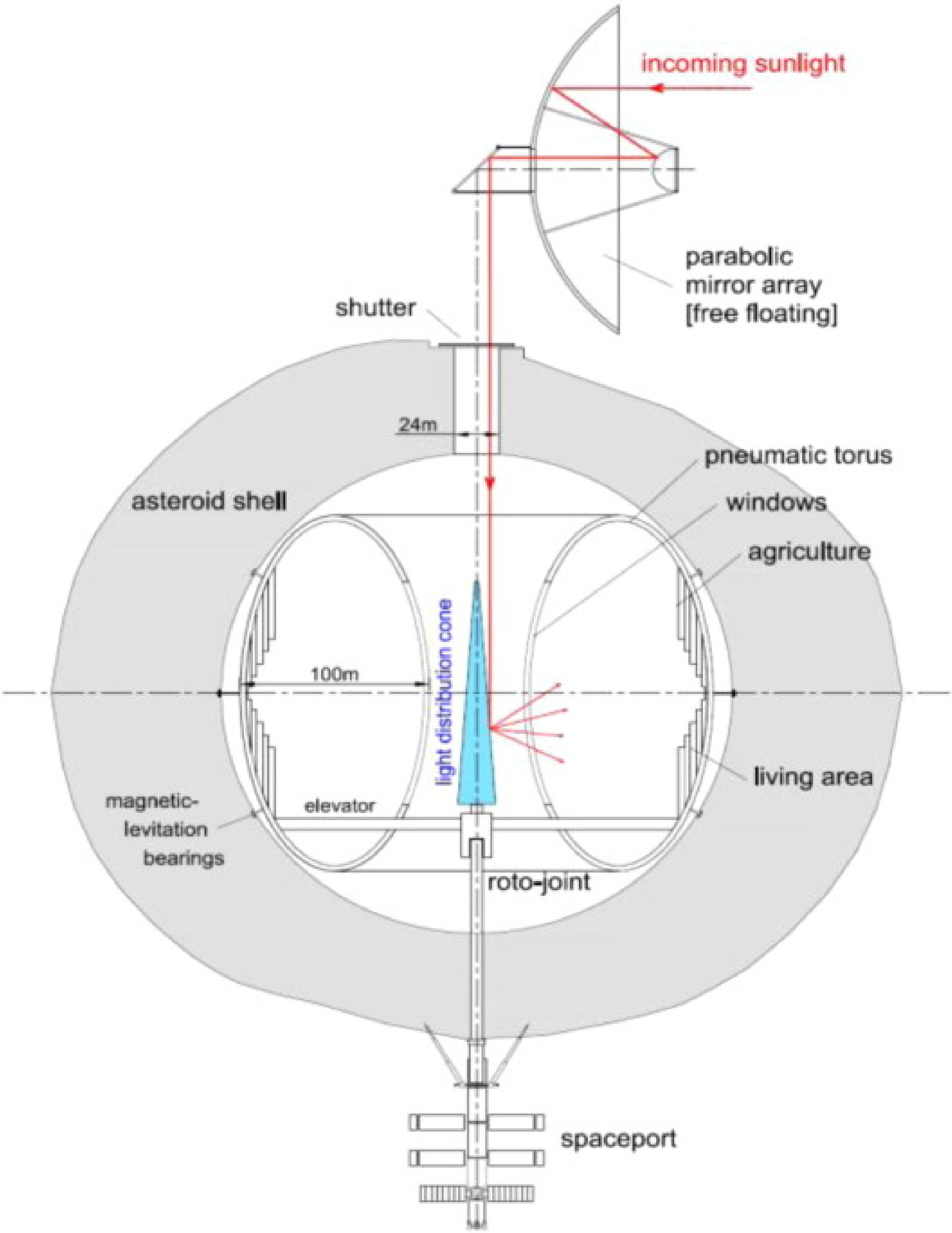

Figure 7.2: A schematic depiction of the envisioned Asteroid Colony, Credits: (Grandl and Bazso, 2013)

acceleration, the radius of the rotating torus should be at least 100m. (Grandl and Bazso, 2013; von Puttkamer, 1987) Therefore, an asteroid of at least 400m should be chosen to conduct such an operation. The torus itself has been proposed, to be built of prefabricated pneumatic elements that can be inflated once inside the asteroid. For natural illumination, a set of parabolic mirrors could beam sunlight into the center of the asteroid, where it can be distributed into the torus by a central mirror cone. The array of parabolic mirrors is designed to be a free floating set outside the asteroid with an independent rotation. (Grandl and Bazso, 2013) The central mirror cone would be equipped with parabolic facets to distribute the light evenly in the torus. To provide up to 90% of Earth's gravitation, the torus would rotate at about 3-4 rounds a minute, which will be achieved by electromagnetic bearings. The spaceport at the asteroid's surface would not rotate, but provide docking stations for inbound spacecraft, and storage modules, which would be derived from the previous mining station. The 'bottom' side of the colony would be used for housing and agriculture, which could hypothetically supply up to 2000 inhabitants. All interior buildings have to be built of lightweight materials like foamed metals, or carbon fibers. The goal of such an endeavor would be to generate a closed water cycle in a hopefully almost self-sufficient colony. (Grandl and Bazso, 2013)

Overall, it can be said that while all these scientific ideas for the exploitation and utilization of asteroids and their residue in space are great, and could potentially help asteroid miners to achieve their goal, there are still many problems left, simply because there are so many unknown factors. It will take many more years to learn how to cope with them, before any realistic approach can be undertaken to actually conduct any form of asteroid mining, be it in situ, or by orbital modification.

Chapter 8

Buiseness strategies

8.1 Companies and strategies

8.1.1 Deep Space Industries

Deep Space Industries (DSI) was formally announced on Jannuary 22, 2013. At the time, they had three spacecraft and patent-pending microgravity manufacturing technologies in development. David Gump, founding CEO, claimed that an early goal of Deep Space Industries was to set up a system to refuel communications satellites that contain a refueling interface. As a long-term plan, the development of space colonies and vehicles from resources gathered by asteroid mining was envisioned.(NASA, 2013b; Rincon, 2013; Space.com, 2013; L'Eatourneau, 2013) In 2013, DSI hoped to be able to begin actively mining asteroids for metals and water by 2023. The water would split in hydrogen and oxygen to generate rocket fuel, which would be stored and used in outer space, either refueling communications satellites or to refuel spacecraft (manned or unmanned) which then travel to Mars. This would save a lot of fuel for such operations, as it would save considerable amounts of transport weight on the journey from Earth's surface to its orbit. To set up a system to gather information on asteroids, DSI is currently developing a series of space probes called FireFly, which was already reviewed previously.

It can be assumed that the strategy of this company is to first focus on the extraction and retrieval of water from asteroids, gathering a deeper understanding of how to optimally conduct asteroid mining, while the exploitation of asteroid metals is most likely postponed, as it requires more sophisticated technology and know-how.

8.1.2 Planetary Resources

Planetary Resources Inc., formerly known as Arkyd Astronautics, was formed on 1st Jannuary 2009, and renamed and reorganized in 2012. Although its long-term plan is rather close to that of DSI (conducting asteroid mining first for water that can be stored in space for refueling purposes), its approach and short-term goals are different. Planetary Resources plans to gather the information required for asteroid mining not by sending small space probes to asteroids, but instead launch a series of small (30-50kg) cost reduced space telescopes into Earth orbit from where it will start a large survey. These telescopes capable of researching NEOs will also be sold to potential customers like NASA, ESA or JAXA. (Efrati, 2012) So far, they have already successfully tested some of the Arkyd class satellites, which were also briefly reviewed previously.

8.2 Rationale of exploiting asteroids and profiting

While such plans are necessary for conducting asteroid mining, a concept of exploitation does not suffice to make profit with it. The financial feasibility of asteroid mining depends not only on the availability of cheap propulsion systems and machinery for asteroid mining, but also on the prices that can be achieved on the markets with the gathered resources. There are two different markets on which the resources may be sold: the space market, and the terrestrial market. In space, most resources are considerably more valuable, as the space price is calculated by taking the terrestrial price, and adding the cost of transport to space. Within near future the cost of transport will most likely decrease to some 15,700$\$/kg$. (SpaceX, 2017) However, currently it is still considerably higher. As the resources gathered by asteroid mining pose no additional cost whatsoever to deliver to space or LEO, it seems rather preferably to sell resources on the space market, especially the less valuable ones that would result in no profit if sold on terrestrial stock market, such as iron, or water. Currently however, there is no space market, as it first needs to evolve. One of the only resources that can be gathered from asteroids that already has a demand in space is water. It can be processed into rocket fuel, or used to sustain the crew of the ISS. Any other resources like iron, nickel, cobalt, REEs, or PGMs however, can currently not be processed in space, and therefore have no practical use there. Thus, they will have to be sold on terrestrial markets instead, at least for the time being.(Sommariva, 2015)

Due to the prices of the different resources reviewed in this thesis, only a small minority of them will yield the major fraction of profit on terrestrial markets. Thus, PGMs and some precious metals like gold are marketable on Earth to make asteroid mining lucrative, whereas the price structure of most industrial markets does not make them that commercial on Earth. PGMs are considered 'critical materials', which usually refers to materials whose demand is high, which are marketed on a global scope, and whose supply is constrained. The demand of PGMs has not only increased by about 5.5% on average during the last 60 years, and is expected to increase at an average rate of about 4% annually within the next decade.

(Sommariva, 2015) Currently 25-30% of the worldwide demand for PGMs is due to industrial manufacturing, while the rest is used for jewelry. As environmental legislation affecting global emission standards will most likely extend to large developing countries like China and India, the use of catalysts will be one of the most grievous impactors on global demand, which will result in a larger fraction of industrial demand for PGMs on a global scale. (Sommariva, 2015)

The supply side is however, what really makes asteroid mining profitable. Criticality is the consequence of a confluence of different factors. The first being physical limitation, which is the scarcity of PGMs in Earth's crust, secondly, the influence of non-primary market actors like governments, and thirdly the fragility of resource supply chain to disruptions from operating dislocations. The last can be either of stochastic (natural disasters etc.), organizational (labor unrest, governmental policies etc.), or institutional (non-competitive behavior of firms) nature. The different factors vary between different materials. Criticality can sometimes be the consequence of sheer scarcity of a material, however more often it is the consequence of supply concentrations within only a few areas worldwide, which often results in a monopolistic or oligopolistic situation resulting in extreme market pressures. (Sommariva, 2015) For PGMs, the scarcity results in a more profound problem. As the typical ore grade of PGMs is around 0.5-3g/t, orders of magnitude lower than average grade of copper, iron, or zinc. This leads to extremely high production costs due to the energy required for processing. To treat 1kg of PGMs around 240 Giga Joule of energy are required, which is a lot more than for any industrial metal. With upcoming environmental restrictions, any volatility in energy prices would amplify the volatility in PGM prices. (Sommaravia 2015) Further, only four companies control over 50% of total global supply, indicating a strong oligopolistic situation. Coincidentally, the largest deposits of PGMs lie within politically unstable countries like Russia, Zimbabwe, and South Africa, where labor unrest and energy shortages caused the largest fraction of global price volatility. (Sommariva, 2015) Any disruptions in these countries could affect 95% of worldwide PGM supply in the future. To safeguard against such a dependency on only a few countries, new deposits would have to be found and explored, which costs a lot of money, and undermines efforts to increase supply chain cost efficiency. Studies have shown, that while managers often look displeased on costly price volatilities disturbing the productivity of their companies, most have done very little to mitigate their impact. (Sommariva, 2015; Tang, 2006) The development of an off world supply in PGMs could provide an effective tool to reduce the fragility in supply chain of these resources, at least under certain circumstances and if conducted with financial feasibility in mind.

As the prices for certain materials are extremely volatile, the sheer amount of

PGMs for example, mined from a large M-type asteroid, might crush the world price. Especially for PGMs it can be assumed that the demand is in-elastic in the short term to the supply, which creates a situation where a significant increase in supply may have a large negative impact on the price. (Sommariva, 2015) This could even lead to a net loss of the entire asteroid mining venture, if the calculated price necessary for making it profitable can not be achieved. Therefore, it may be preferable not to sell the entire stock of resources gathered at the same time so the price volatility is not enhanced. To achieve a modest price volatility, an asteroid mining company should try to negotiate a fair market share with other suppliers of the respective resource. (Sommariva, 2015) As a negative impact on the resource price would weight as heavy on terrestrial suppliers as on asteroid mining companies, this may be a good enough reason for even monopolistic companies currently controlling the world market to be forced into negotiations. This could result in an outcome where terrestrial and off-world suppliers can maximize profits. If however, the terrestrial suppliers should choose not to negotiate, asteroid mining companies should look for a multi-period optimization where they can react to the supply generated by the dominant oligopolistic companies. Data inferred by companies past actions and offers can help adjusting the own offer for next selling periods, which would result in an incomplete adjustment in the single periods, however could help establishing a long term quasi equilibrium in supply compared to the world demand. In any case, asteroid miners should find agreements with service companies that store their resources to gradually sell them over time. The service company could thereby act as a liquidity provider and sales agent, freeing the asteroid mining company's resources to conduct asteroid mining, while the market conditions are of no consideration to them. (Sommariva, 2015) This could even go so far that the service company acts as an additional market volatility buffer providing a stable, yet mid to long term lower price, which the asteroid mining company can achieve by directly selling huge quantities to them. This would help the asteroid mining company to reduce risk of dropping prices, while also creating a lucrative trading option on the stock markets.

The last option would further minimize the risk of being targeted by investigations by the competition authority due to illegal pricing agreements.

However, the pricing is not the largest legal problem considering asteroid mining so far, as the regulation for enterprise activities in outer space are still somewhat crude.

Chapter 9

Regulations

The most important regulations creating a legal framework for any operation or venture conducted in outer space is a set of international treaties. They have been negotiated during the dawn of space exploration during the cold war. The first treaty was the outer space treaty that summarizes the principles based on which the international community, as well as single nations are allowed to use the outer space. As space became more and more important for mankind and the international community, more precise treaties were formulated to set an international standard for rescue and liability, and to further limitations to any kind of national law. Naturally, fewer and fewer countries signed and ratified these following treaties due to their strictness.

Overall there is no real 'space law' as most aspects referred to in the treaties, are either not relevant as only a few countries signed them, or extremely vague, leaving a lot of room for interpretations by both private, and national parties. The crudeness which is especially apparent in the first treaties can easily be attributed to the fact that both dominant world ideologies socialism and capitalism did try to find the smallest principles they have in common, and not giving anything away to the other. Therefore, the vague nature of these treaties is simply due to the lack of consensus between the parties, and most likely also due to the fact that back in the sixties most negotiators probably did not think that we could need international regulations for asteroid mining in the two thousand twenties.

9.1 Outer Space Treaty

The outer space treaty, formally known as Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, is the base of international space law. It was opened for signature in the United States of America, the United Kingdom, and the Soviet Union in 1967, and entered into force that same year. Until September 2017, 107 countries have ratified the treaty, and 23 more have signed it preparing ratification in accordance to their own national law. (UNOOSA, 2018a) Among the principles it follows, and also one of the main goals of the negotiations is the ban of stationing weapons of mass destruction in orbit of Earth, the Moon or any other celestial bodies. This is mostly owed to an immanent fear of nuclear war between the Soviet Union and the US. It further prohibits the use of celestial bodies for testing weapons, conventional just as weapons of mass destruction. (UNOOSA, 2018a)(Article IV)

As there are however too many articles in the outer space treaty to review all of them, only the articles that may be interesting for asteroid mining are described in this section. The outer space treaty also exclusively limits peaceful activities of celestial bodies. The treaty states that the exploration and use of outer space shall be only done to benefit all countries and all of humankind, and that it shall be open for exploration and use by all states. (UNOOSA, 2018a)(Article I) It also explicitly states that outer space, including the moon and any other celestial bodies are not subjects to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means. (UNOOSA, 2018a)(Article II)

As a legal framework, it also regulates responsibilities and sets standards for the applicability of national law in space. Article VI states clearly that parties to the treaty shall bear international responsibility for any national operation in outer space, whether these are carried out by governmental organizations or non-governmental entities. The activities of non-governmental entities in outer space require authorization and continuing supervision by the appropriate State Party to the treaty. Article VII says that each State Party to the Treaty that launches or procures the launching of an object into outer space, and each State Party from whose territory an object is launched is internationally liable for any damage the object may cause. For the case of asteroid mining, this would make national laws necessary to regulate any mining activities, as the countries from which the operations are conducted and launched, are internationally responsible for any failure that involves collateral damage. Article VII further grants each State Party to the treaty the right to retain jurisdiction over any vessel that is launched under its jurisdiction. The biggest legal problem posed by the international space treaty for the operation of asteroid mining vehicles is therefore the lack of sovereignty, which could make any spoils gathered by the machinery an illegal claim, as there is no law regulating that, with the addition of a prohibition of any national law being allowed to regulate it.(UNOOSA, 2018a,b)

9.2 Follow-op treaties

As the Outer space treaty is rather vague in many cases, follow-up treaties and agreements had to be negotiated to set rights and obligations into an operational set of regulations. Namely there are three treaties that have relevance: the Rescue Agreement, the Space Liability Convention, and the Registration Convention.

9.2.1 Rescue Agreement

The Rescue Agreement was adopted by the UN General Assembly on 19 December 1967 through Resolution 2345. It entered into force in 1968, and was ratified by 92 States and 24 more have signed it. (UNOOSA, 2018b) The Rescue agreement states that astronauts are to be rendered all possible assistance by State Parties to the treaty. It was mainly created to add some clarity to issues of the outer space treaty, by including any personnel aboard a spacecraft, instead of just referring to astronauts, which has never been strictly defined in a legal sense. The rescue agreement therefore states generally, that any person aboard a spacecraft needs to be helped by any State Parties to the treaty, if in troubles. (UNOOSA, 2018a)

9.2.2 Space Liability Convention

The Space Liability Convention expands on the liability rules created in the Outer Space treaty. It was concluded and opened for signature in 1972. 89 States have ratified the Convention, and 22 more have signed it. It says that States are responsible for any space objects that are launched within its territory. If two states work together to launch a space object, they are jointly and severally liable for any damage the object may cause. It further clarifies that claims under the liability convention must be brought by state against the state. It was therefore created to supplement national laws, providing compensation to any parties injured by space activities. This was necessary, as in most legal systems any individual or corporation may bring a lawsuit against another individual or another corporation, whereas the liability convention takes this to a state level only. (UNOOSA, 2018a)

The Registration Convention was adopted by the UN General assembly in 1974, and went into force in 1976. It has been ratified by 64 states, and four more have signed it. It forces states to register any space vehicle to travel under their flag. Like the other additional treaties to the outer space treaty, it has been designed to compensate some of the crude rules and declarations of the outer space treaty, and provides a register on any space object launched. The register is kept by the United Nations Office for Outer Space Affairs, and includes the name of the launching state, an appropriate designator of the space object or its registration number, date and location of launch, basic orbital parameters, and the general function of the space object. Any information on registered objects can be found at the UNOOSA site. (UNOOSA, 2018a,b)

9.3 Moon Treaty

The Moon treaty, is the last treaty governing the affairs of outer space, that was concluded in 1979. The basic idea behind it was to turn over the jurisdiction of al celestial bodies including the orbits around these bodies over to the international community. All activities around celestial bodies therefore would have to be conform to international laws, including the moon treaty itself, and the United Nations Charta. It can be considered a more strict version of the outer space treaty, as it explicitly prohibits any military use of outer space, including military bases, presence of weapons et cetera. However, most striking is the difference regarding the civilian limitations it poses. It bans any exploration and uses of celestial bodies without the approval or benefit of all other states. The Secretary-General must be notified of all activities in outer space, and all discoveries that result from them. It declares that any samples gathered during such activities must be made accessible to scientist all over the world (at least partly). It bans altering the environment of celestial bodies, requiring exploring states to prevent any contamination. It requires an international regime to be set up, which ensures safe and orderly development and management of resources and sharing the benefits resulting from any space activities. (UNOOSA, 2018a,b)

One of the most notable differences to the outer space treaty however is the common heritage principle defined in article 11. This claims all of space as a common heritage of mankind, making it not only illegal for states to claim sovereignty over any celestial body, but also explicitly bans any ownership of any extraterrestrial property by any organization or private person. This treaty makes asteroid mining strictly illegal, as any mining activity would necessarily result in the destruction of an asteroid's environment, but also denies any legal claim over the resources gathered during the process. (UNOOSA, 2018a)

Since 1979, 7 states ratified the treaty, with 10 more having signed it. While in reality, it can be regarded a failed treaty, as only a few states have actually ratified it, none of which is capable of conducting any manned space exploration or exploitation operations. (UNOOSA, 2018a) While it therefore has only negligible influence on international affairs in outer space, it is still worth mentioning, as any company planning to mine asteroids should consider not to travel under the flag of any country participating in the treaty. This means that the registration country should be one amongst the nations who have absolutely ignored any idea of a common heritage principle of outer space.

9.4 National Law

The vague nature of any relevant outer space treaty, agreement, or convention makes national laws necessary to either allow or ban asteroid mining, as no international lawset is designed to regulate such activities (Most likely because nobody in the 70s imagined asteroid exploitation). Calling the outer space treaty 'vague' is only correct in a legal sense. Most people would conclude that the prohibition of any national claim of sovereignty over any celestial body (UNOOSA, 2018a)(article II of the outer space treaty) is rather specific, disallowing any nations to pass laws recognizing private property on any soil that is per definition not under the control of said nation. However, the treaty fails to define the object of its application. The lack of any concrete definition has therefore sparked a dispute in the specialized academic community. This dispute is about the legal definition of 'space' and 'celestial bodies'. This question has first been brought up by eight equatorial countries that claimed their right to exercise national sovereignty over the segments of the geostationary synchronous orbit (GSO) located over their territories. (Pop, 2013) Pursuant to the non-appropriation principle of Article II of the outer space treaty, asteroids cannot be appropriated as long as they are viewed as celestial bodies. If however them being celestial bodies was questioned and defined otherwise, any nation that has not signed the Moon treaty has no international restriction in granting private claims over the floating resources called asteroids. (Pop, 2013) An alternative was not to view asteroids as something else than celestial bodies, disallowing them to grant private claim over the asteroid, but instead granting private claim over any spoils gathered from asteroids. The asteroid itself may be consumed in the process, however it does not need to be the company's property, as long as it is nobody else's property either. This loophole in the outer space treaty is a more elegant way to by-pass the prohibition of claiming sovereignty.

Some nations have done just that: passing laws to give private persons or companies the right to claim resources gathered from asteroids as their property.

9.4.1 United States

President Obama has signed the US Commercial Space Launch Competitiveness Act (GSLCA) in 2015 following Congress' approval. The GSLCA explicitly allows US citizens to engage in the commercial exploration and exploitation of 'space resources' including water and minerals. To not contradict the outer space treaty, the bill further asserts that the US does not assert sovereignty, or sovereign or exclusive rights or jurisdiction over, nor the ownership of any celestial body. (Orphandies, 2012) Further, the space act includes the extension of indemnification of any US launch providers for catastrophic third party losses due to a failed launch until 2025, and extends the 'learning period' restrictions, limiting the Federal Aviation Administration's ability to enact regulations considering the safety of flight participants. (Foust, 2015) This shelters companies such as SpaceX trying to commercialize space launches.

9.4.2 Luxembourg

In 2017, Luxembourg's parliament voted almost unanimously in favor of the new space mining law. Luxembourg's bill is relatively close to that signed by President Obama in 2015, and grants legal claim to all minerals and materials mined from space without claiming sovereignty over the celestial body from which they stem. Together with massive governmental aid to companies trying to facilitate in asteroid mining, Luxembourg is trying to set up a massive space industry in the Grand Duchy. It is the first European country, and one of the first in the world to pass bills in favor of asteroid miners, yet undoubtedly more will follow, once the realization of asteroid mining has come near. (PlanetaryResources, 2018)

Chapter 10

Future of asteroid mining

With the jurisdictional problem out of the way, at least in some countries so far, asteroid mining has come a step closer towards realization. The exact timeframe in which the conduction of mining operations can start remains highly uncertain and depends on various factors such as the investments of the companies, scientific progress, and innovation in overcoming the different problems posed by the harsh environment of asteroid surfaces.

10.1 Main Problems

One of the largest currently known problems for asteroid mining lies in the significant gaps in our scientific knowledge about asteroids. These gaps stretch from the already reviewed uncertainty in establishing links between asteroid and meteorite classification systems, over the classification rate of asteroids, which lags far behind their discovery, to the unknown internal structure of asteroids and the unknown behavior of their regolith under a microgravitation environment. However, there are also technical problems which require some innovative solutions, like the problem considering the cooling of mining machinery in outer space.

10.1.1 Asteroid discovery/classification rate

The rate of asteroid discovery is by far higher than the rate of their characterization. Within the last years, asteroid discovery has significantly increased and is currently at about 1000 objects a year on average. This is mainly due to the telescopes looking for them being by far more sophisticated than a few years ago, growing more sensitive by 1mag every 7.5 years. (Galache et al., 2015) Discoveries of large asteroids however, have remained rather stable at around 365 /year over the past decade. At this rate alone, the discovery of 90% of the NEO population larger than 140m which was mandated by the US congress to be achieved until 2025, will only be met a decade late, approximately in 2035. (Galache et al. 2015) For asteroid miners this alone is troublesome already, as the only way to conduct asteroid mining especially in the early stages would require locating the potentially most lucrative asteroids there are, before sending space probes towards them. However meanwhile, the characterization of the newly discovered asteroid falls behind farther and farther. Fewer than 10% of the known NEOs have well characterized size, rotation periods, and spectral compositions. At the current pace, it would take at least another century, to classify the NEOs already known, let alone the large population of asteroids that has not been discovered so far. Over 60% of the discovered NEOs have orbital uncertainty parameters of $U \geq 4$, which makes reacquisition after more than a year extremely challenging. For large asteroids, the fraction with highly uncertain orbital parameters is even 90%. (Galache et al., 2015; Graps et al., 2016d) Galache et al. (2015) have argued that the only way for characterization to keep pace with the discovery would be to dedicate telescopes only for that purpose. Visible spectroscopy with an at least 2m telescope would be required to be done within days after discovery, to reduce the risk of 'losing' the asteroid again. (Galache et al., 2015) To provide the data asteroid miners need to prepare the launch of space probes, long-arc astrometry would have to be obtained on telescopes larger than 4m as fast as possible together with fast-cadence light curves. Dedicated telescopes are however not only required to bring up the rate of characterization, but also to react as quickly as possible to the detection of a new object. To provide the optimal data value, the characterization of NEOs requires rapid 'target of opportunity scheduling' which should take place within the same night as the discovery. Such a quick reaction however, is simply not possible at most large telescopes, as their own schedules are extremely full. But a rapid reaction is necessary, as NEOs, especially the small ones, tend to be their brightest and thus best observable, in the moment of their discovery. This makes characterization cheapest when done immediately, as larger and therefore most cost intensive telescopes are required once the NEO decreases in brightness. While this makes the funding of dedicated telescopes critical for asteroid mining conventions, the large discrepancy between discovery and classification so far, requires more efficient observational strategies, than just brute forcing a full IR/Vis spectral characterization for every single asteroid. (Galache et al., 2015)

For asteroid miners who have already obtained control over telescopes sufficient for characterization two different approaches seem preferable.

1. A determination of an asteroid's spectral slopes could be measured with broadband filters. If possible, the use of narrow-band filters could provide more information, however at the cost of the ability to characterize faint objects. Still, the rotational period of asteroids could be problematic when using broadband colors. This is because such observations are usually conducted one filter at a time. The magnitudes are later substracted to derive colors. Since asteroids with low rotational periods can change their magnitude rather fast however (due to a vary-

ing areal composition), the magnitude observed with different filters could end up not being representative. For handling such fast rotators, cameras can be attached to the telescope that obtain observations in multiple filters simultaneously. Such technology exists, however they are currently not widely used. The substitution of full IR/vis spectroscopy with measurements of spectral slopes could significantly increase the rate of characterization. This would only require a sufficiently large sample of asteroids that have been characterized with the full set of available techniques as a reference. (Galache et al., 2015)

2. A step-by-step approach as it is used in planetary defense seems rather useful as well. Thereby an asteroid's orbit would initially be determined right after discovery, accompanied by a filtering of asteroids with a Δv that is too high for the asteroid to be a lucrative target for a mining operation. The initial orbital determination would then be used to track the asteroid for refining the orbital characterization before the object is lost. Simultaneously to the refining of the orbit, the rotation period would be measured. After that, a broadband color observation would deliver information necessary to decide which asteroids seem interesting enough for a closer look. For a few selected asteroids (how many exactly depends on the available observation time), narrowband colors and a full spectroscopic survey can be done. (Galache et al., 2015)

These approaches would save asteroid miners time and thereby money, while also providing the information they so desperately need to choose target asteroids.

10.1.2 Regolith behaviour

Loose-grained materials called regolith, at the surface of asteroids can and most likely will be suspended by landers, or during operations such as mining activities. How exactly this interaction will influence regolith remains uncertain and depends on various factors. In terrestrial mining, the behavior of fine grains is addressed by modulating the mode of extraction with the environment at hand. In mining operations conducted in the deep see, suspended sediments are known to move for hundreds of meters. (Galache et al., 2015; Blondel, 2009)

The behavior of regolith is critical for any kind of asteroid mining, as regolith is the first layer of interaction between any craft and the object's surface. If the grains are blown-off fast enough they may exceed escape velocity and leave the asteroid's surface for good, but if the delta-v isn't that high, they may stay near the asteroid and interact with it and any mining equipment again, as they co-orbit the sun. If too much regolith is orbiting the asteroid, this may even have impact of photovoltaic energy generation, or disrupt more sensitive components. A deeper understanding of the various parameters and processes determining this behavior is therefore an essential information needed. However, our understanding of the subject is limited so far, as the exact behavior depends on the chemical composition of the material, its grid, the grain size, and the exact gravitational force that works on it. The problem about this is that we know neither for sure.

Asteroid regolith is a granular material, which means that it can behave as if it were in three different phases. (Graps et al., 2016a) This leads to some sort of material memory by the building of so-called force chains that can impact micro-gravity even on comparably large distances. (Graps et al., 2016a; Murdoch et al., 2015) Since some asteroids are thought to consist of a large fraction of regolith, this may lead to catastrophic complications, as a perturbation on one side of the asteroid can be felt on many distant locations on the asteroid, which could even affect its overall stability. Unstable asteroid surfaces may be quite common. Unfortunately, it is rather hard to find out more about regolith behavior, especially under micro-gravity environment.

The only way to study a regolith's cohesive strength and its mechanical properties is to directly interact with it. While this can be done with a mining robot, it is necessary to gather said information beforehand. Any mission to asteroids that includes coming into direct contact with the asteroid's surface can tell us something about these properties. This can either be achieved by observing, how either a lander bounces on the asteroidal surface as it is planned in the Hayabusa 2 mission, or by directly impacting on the asteroid like the AIDA mission plans to do, or via the response to a sampling tool, or any seismic experiment. Currently however, we have very little information of how regolith responds to any external action in a micro gravitational environment. This makes the above mentioned missions absolute necessary before asteroid mining can become reality. (Biele et al., 2016; Graps et al., 2016a; Michel et al., 2016) These missions will not deliver information that can be directly used to prepare for entirely different asteroids, but instead only give us insight into how the actual space environment influences the behavior. The different compositions of regolith, and their influence on its behavior still need to be researched intensively. However, once it is known how the low asteroid gravity determines its behavior, the rest can be done with experiments on Earth, where the various compositions of asteroid regolith can be simulated in the lab. Still, to gain a high level of certainty, the simulations need data acquired by sampling missions to optimally recreate asteroid regolith compositions on Earth. Such sampling missions could be the Hayabusa2 or OSIRIS-Rex. (Graps et al., 2016c; Metzger et al., 2016; Graps et al., 2016b)

As of now, there are still many considerations of making simulants with a sufficiently high fidelity to be useful.

1. Only little information has been published so far about bulk composition of meteorites, the only objects in our reach that are sufficiently massive to represent asteroid composition. This may be mostly due to the very high prices of meteorite material, which would necessarily have to be destroyed in the process of deriving information about bulk composition. Every simulant bases on the few bulk compositional analysis that has been done.

2. The organic content of asteroids is impossible to replicate, and is currently replaced by the use of kerogen or sub-bituminous coal.

3. There is no sufficient data on the particle size of asteroid regolith. Currently laboratory experiments are conducted based on rough estimations, making their outcome rather speculative.

4. While mixing the correct minerals the resulting simulant produces the desired albedo, however the reflection spectra of these simulants has so far not been investigated.

While there are still many more additional properties that have not yet been replicated, this is currently the best that can be done with the limited information at our hands. (Graps et al., 2016c; Metzger et al., 2016; Graps et al., 2016b; Delbo et al., 2014)

10.1.3 Cooling of machinery

While there are many technical problems lying ahead of asteroid miners, only one will be described in this thesis. The cooling of machinery in outer space is most likely going to be one of the most challenging. Drills and tunnel boring machines tend to produce a lot of heat by friction. In fact almost the entire kinetic energy used for drilling will be subsequently transformed into thermal energy with the only exception for the small fraction that stays kinetic in form of small particles being accelerated. On Earth the heat is easily dispersed by cooling equipment that uses the cooler atmosphere to take up excess thermal energy over convection. As asteroids do not have any atmosphere, all of the thermal energy needs to be reduced by the more inefficient radiative heat transport. This would require extremely large thermal radiation areas, making the entire equipment that much heavier. Still, these technical problems are of no immanent concern. The CEO of Deep Space Industries, Bill Miller, claimed that they will not have a look into the subject of cooling systems for another couple of years (private communication)

10.2 Martian and lunar mining robots

As can be seen from previous sections, material strength of the minerals in questions makes the mining of ores on asteroids rather difficult, as it requires a complicated mechanical approach towards automatization and mining under a space environment, than the mining of volatiles such as water. The mining of volatiles thus seems a logical first target that enables asteroid miners to gather vital information on asteroidal environment in situ while also making profit by producing fuel and water to supply paying customers like companies that want to refuel their satellites, or the ISS.

Since many of the problems with conducting asteroid mining for minerals and ores involve the lack of experience in mining under a space environment, other celestial bodies like the Moon or Mars seem an ideal testing facility for mechanical mining, as their environment itself is comparable to that of asteroids in terms of the lack of an atmosphere, and the harsh radiation. The main difference is a higher gravitation, diminishing any obstacles like a low escape velocity, and the unknown regolith behavior under micro gravitation, while still allowing for the development of mechanical mining machinery that could later be used for asteroids as well. This would have the benefit that asteroid miners, or in this case 'space miners' could concentrate on coping with separate sets of problems.

This could make mining operations on Mars and Moon a vital next step towards the realization of ore mining on asteroids.

The idea to build and use martian mining robots has already been brought up under different circumstances by Elon Musk. While he does not plan to conduct martian mining missions to further the technical experience in space mining, he plans to do so to gather ne necessary resources in situ for his ambitious goals to colonize Mars. (Jamasmie, 2016)

Chapter 11

Prospects for science

11.1 Financial influence on scientific progress

In the case of asteroid mining, science and private sector operators will profit from one another. Scientists can gather the data on many fields that asteroid miners do so desperately need, like regolith behavior, compositional characterization and development of new propulsion systems, while the private sector has the financial power to supply even extremely expensive projects. This could help reducing the traditional problems of scientists in the financial sector. Further, asteroid miners themselves will have to conduct many surveys on asteroids, which will generate a lot of data for scientists to work with, helping science to better understand the mechanics of asteroids. For the first time in history, there is a great financial interest in space beyond Earth' orbit, which will inevitably lead to a symbiosis between private companies and science, as it did in molecular biology decades ago.

11.2 Planetary protection

Another great prospect for science and mankind itself is that the necessity of finding lucrative targets for asteroid mining ventures will automatically lead to an extremely well-funded and precise mapping of asteroids within the inner solar system. This is necessary, as many large asteroids remain undiscovered despite governmental mandates to locate any potentially dangerous asteroids. The fate of the dinosaurs has already impressively proven the potentially hazardous effects of a large asteroid impacting Earth and there is little reason to believe that we would not suffer similar devastation if such an object would impact Earth today. Asteroid mining would thereby help in two different ways. Firstly, the detection of asteroids and the determination of heir orbits would enable us to predict impacts possibly years and decades in advance, which would significantly increase our chances to avert a tragedy. Secondly, the most lucrative targets in terms of energy efficiency and body mass, are in many cases those asteroids that would most likely impact Earth eventually, as those are the bodies that come closest to Earth and have a large overall mass, in combination with a high density which is usually a good indicator for an M-type asteroid which boast with PGMs and other valuable resources. Simply mining these asteroids would thereby be a win-win situation, as not only can an asteroid logically not impact Earth if it was mined beforehand, and also generate extreme wealth for the saviors without governments having to spend a single dollar to protect Earth. One of the most powerful motivations is greed, and if there is a profit behind saving Earth, it will most certainly be done.

Chapter 12

Conclusio

My conclusion thus is, that even without He3, there are still many valuable resources stored within asteroids, waiting to be exploited. For the first time in history, mankind could gather resources without damaging or destroying or own environment and therefore habitat. These resources could be used in many different ways, with the most valuable and scarce ones being transported to Earth, and industrial metals eventually used in space. Of course, the development of a space-borne heavy industry is still decades away. Many of the more sophisticated production lines are likely impossible to ever out-source into outer space, such as the production of micro-chips, instruments, propulsion systems and such, but the largest mass fraction for any space vehicles will still be made up of fuel tanks, and heavy radiation shielding, which are comparably easy to produce. This may eventually help in reducing the cost of space vehicles and space operations so far, that we can easily expand into outer space, as every kg that is already produced in outer space will not have to be transported to Earth orbit from its surface, decreasing any mission cost significantly. Especially if an approach similar to the 'asteroid colony' proposed by Grandl and Bazso (2013) would be taken, asteroid mining may even lead to the creation of supply bases all over the inner solar system, helping a great deal to eventually colonize other celestial bodies.

Of course, it is still a long way towards the realization of asteroid mining with many scientific, legal, technical and financial problems laying ahead of it, yet the increasing depletion of EarthâĂŹs crust in resources will make it more and more profitable. Many companies have announced eager goals to conduct asteroid mining within years, but considering the obstacles, decades may be a more reasonable time frame for the industrial exploitation of all asteroidal resources. As the mining of volatiles on asteroids requires only a few mechanical components and relies more heavily on heating of material by using solar energy, this seems like a reasonable first step in asteroid mining. A parallel approach where asteroid miners start to conduct simple mining of asteroid volatiles while simultaneously gathering more information about asteroid characteristics seems preferable, as most experience has always been gained by doing.

The first targets will most likely be potentially hazardous objects (PHOs) and other NEOs, as they require the least energy to reach which significantly reduces the overall payload of fuel, leading to a cheaper exploitation, thereby maximizing the profits gained by operations. However even the exploitation of main belt asteroids will eventually be plausible. As mining of potentially hazardous objects possibly threatening Earth in the future goes hand in hand with mankindâĂŹs natural interest in protecting our planet from dangerous impacts, even multi million financial aids and benefits could be expected to come from governments. Considering the mutual benefits in both planetary defense, as well as the exploitation of resources in an environmental friendly operation, this would be a logical step for governments to do. The United States of America have already helped a great deal by easing the regulations imposed on industrial interests in advancing experience in conducting private sector activities in space, and the state of Luxembourg has already approved a million-dollar heavy investment in asteroid mining companies. Other states will most likely follow their example or risk losing grip on this newly developing industrial sector and thereby giving up the opportunity on potentially substantial tax income later-on. Hypothetically any country can hope to take part in future asteroid mining operations, at least as the legal authority regulating the spacecraft operating under their flag, except those who have signed or ratified the Moon Agreement, which explicitly prohibits the granting of claims on any resources gathered in outer space. However, with the exception of India there is no participant in this international treaty with any experience in the conduction of space operations, or any hope to do so within the near future.

Once asteroid mining provides the first resources to terrestrial markets, a careful evaluation of strategic economical positions and interests is necessary. The sudden flow of potentially hundreds of tons of valuable and previously scarce minerals and metals into the economy could destabilize the prices and therefore the economical feasibility of asteroid mining, and could have a grave impact on financial stability, as many of the materials in question are currently deemed resources of strategic interest, and are in many cases seen as a lucrative long-term investment opportunity. As strong market fluctuations are in no oneâĂŹs interest, especially not in that of companies investing in the conduction of operations that take years to plan and execute, it is most likely that mutually beneficial approaches are sought that are in the interest of any economical participant in the sectors in question. Still, the economical side of asteroid mining should not be underestimated, and strongly considered in any plans, as the lack of lucrativeness has proven to be extremely effective in shutting down otherwise great ideas. Especially in the case of asteroid mining, which is an existential next step for mankindâĂŹs advance into space, and thereby should be of vital interest for any government, this would be a terrible situation. Either way, science can be considered to be one of the big winners of asteroid mining, as the exploration and scientific evaluation of asteroids finally has a financial interest backing these ambitions. Questions that have been around since the birth of asteroid science could finally be resolved, such as the true origin of meteorite classes, the determination of asteroid compositions leading to a deeper understanding of the evolution of our solar system itself, and insights into the chaotic orbital behavior of the smallest celestial bodies in our vicinity. Whether the data is acquired by mining companies and sold to governmental and international scientific organization, or acquired by scientists financially supported by private sector companies, does not matter in the end for their significant impact on the advance of our knowledge and understanding of our solar system.

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