



Cloudy with a chance of near-Earth asteroids

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Introduction

In this paper, a brief overview with regard to near-Earth asteroids will be provided. The first chapter will be dedicated to a description of asteroids in general, as well as to a definition of near-Earth asteroids.

The second chapter will elaborate on the potential threat of an asteroid impact. In particular, attention will be given to the monitoring of so called potentially hazardous asteroids, with remote sensing techniques from Earth and space. A closer look will also be taken at several planetary defence initiatives.

In the following parts, the more positive aspects of asteroids will be examined. Firstly, the valuable scientific information that asteroids contain. Multiple exploration missions that performed asteroid flybys will be mentioned. Furthermore, three missions to near-Earth asteroids will be discussed.

The fourth and final chapter gives consideration to the commercial opportunities of asteroids. These will be illustrated with a specific mission of a space mining company.

1. Asteroids

Asteroids are small, rocky remnants left over from the early formation of our solar system that began some 4,6 billion years ago, when a big cloud of gas and dust collapsed. While most of the material fell to the centre of the cloud, forming the Sun, some of the residual matter in the cloud formed planets. However, some leftovers from that process never had the chance to be incorporated into such planets.

As opposed to the spherical shape of planets (where liquid or even gas forms an even sphere around the gravitational centre), asteroids have irregular shapes. This is because they are much smaller and do not respond well to their own weak gravity. Only the largest exemplars possess enough gravity to pull them into spherical shapes. Dimensions also vary from hundreds of kilometres in diameter (Ceres has a diameter of approximately 945 km and represents more than a quarter of the entire mass of the main asteroid belt) to the size of a pebble stone (the smallest asteroid ever studied was however still 2 m wide).

It is assumed that all asteroids are derived from only a few hundred protoplanets. These were large enough to melt inside and allow heavy metals to sink to their centres. Over billions of years, these protoplanets collided and broke up during numerous impacts, forming the asteroids we observe today. These are mainly gathered in the main asteroid belt, a vast doughnut-shaped ring between the orbits of Mars and Jupiter. When Jupiter was formed, its massive gravity brought an end to the formation of bigger planetary bodies in this region and caused the small bodies to collide with one another, fragmenting them into millions of smaller asteroids. The belt is estimated to contain between 1.1 and 1.9 million asteroids larger than 1 kilometre in diameter, and millions more of smaller ones. Although this is an enormous number, the total mass of the asteroid belt combined equals only 4% of the Moon its mass.

The current understanding of asteroids has been derived from three main sources: laboratory analysis of meteorites, Earth-based remote sensing and data from mission flybys or encounters. From these sources, it is clear that the composition of asteroids can differ a lot. They are therefore classified into different types according to their albedo, composition and similarities to known meteorite types. The albedo of an object measures the light reflection or intrinsic brightness. A white perfectly reflecting surface has an albedo of 1, a black perfectly absorbing surface has an albedo of 0. When applied on asteroids, this measurement can give indications on the composition. Based on compositional differences, several types of asteroids can be distinguished.

The typical composition of an asteroid depends on its distance from the Sun. Three main types can be characterised. The C-type (carbon) asteroids are most common and include more than 75% of known asteroids. Consisting of clay and silicate rocks, and with surfaces that are almost coal-black, they are dark in appearance with an albedo of 0,03-0,09 (reflecting less than 10 percent of the sunlight that falls on them). These are composed of hydrogen, helium, and other volatiles. They also contain a large amount of water molecules, but hardly any metallic elements. C-type asteroids inhabit the main belt's outer regions (approximately at 3 AU from the Sun) and are among the most ancient objects in the solar system. The S-types (stony) account for about 17% of known asteroids. Their composition is of metallic iron mixed with iron- and magnesium-silicates, but they barely contain any water. These are relatively bright with an albedo of 0,10-0,22. S-type asteroids dominate the inner asteroid belt (the region closest to the Sun, approximately at 2 AU from the Sun). These include similar components of stony planets such as Earth and Mars. Lastly, the M-types (metallic) include most other known

asteroids. These are also relatively bright with an albedo of 0,10-0,18.¹ They can contain rare metals, such as platinum. M-type asteroids inhabit the main belt's middle region.

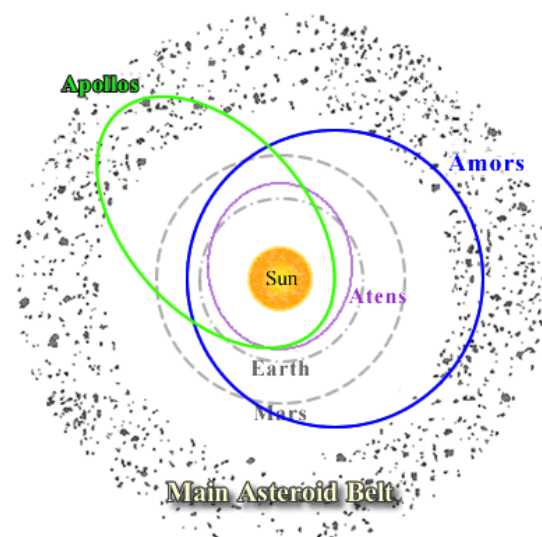
Composition aside, other structural variations of asteroids exist. Some are rather rubble piles than solid objects. This means that they are loose collections of pieces, held together by the force of their gravity. These asteroids were formed in collisions. Moreover, an increasing number of asteroids are being found to be doubles. This phenomenon occurs when two similarly sized asteroids drifted together to orbit around each other, sometimes even touching, as they share a path around the Sun.²

1.1 Near-Earth asteroids

Asteroids whose orbits bring them relatively close to the Earth (perihelion distances of less than 1,3 AU), are known as near-Earth asteroids (NEAs). NEAs were knocked out of the main belt and hurled into space across the orbits of the other planets. This happened through either collisions between asteroids or by the gravitational influence of Jupiter. Roughly 20 000 NEAs have been discovered, but many more are still undiscovered. With a mean diameter between 30 and 40 km, the largest presently known NEA is 1036 Ganymed. The NEA population appears to be representative of all three mentioned asteroid types found in the main belt.

Based on their orbit, there are three main groups of NEAs. Atens Asteroids (which cross Earth's orbit with a period less than 1 year), Apollo Asteroids (which cross Earth's orbit with a period greater than 1 year) and Amor Asteroids (Earth approaching asteroids with orbits that lie between Earth and Mars).³ One could add Inner Earth Objects as a fourth type, consisting of 6 asteroids that remain inside of Earth's orbit.

NEAs only survive in their orbits for 10 million to 100 million years. They are eventually eliminated by orbital decay, collisions with the inner planets or by gravitational ejection from the solar system after near misses with the planets. They are resupplied on a regular basis by orbital migration of objects from the asteroid belt.



NEAs have orbits which bring them relatively close to Earth. The 3 main groups are distinguished by their orbital characteristics which are illustrated here.

¹ NASA Science, Solar System Exploration, <https://solarsystem.nasa.gov/asteroids-comets-and-meteors/asteroids/in-depth/>, retrieved: 27 December 2018.

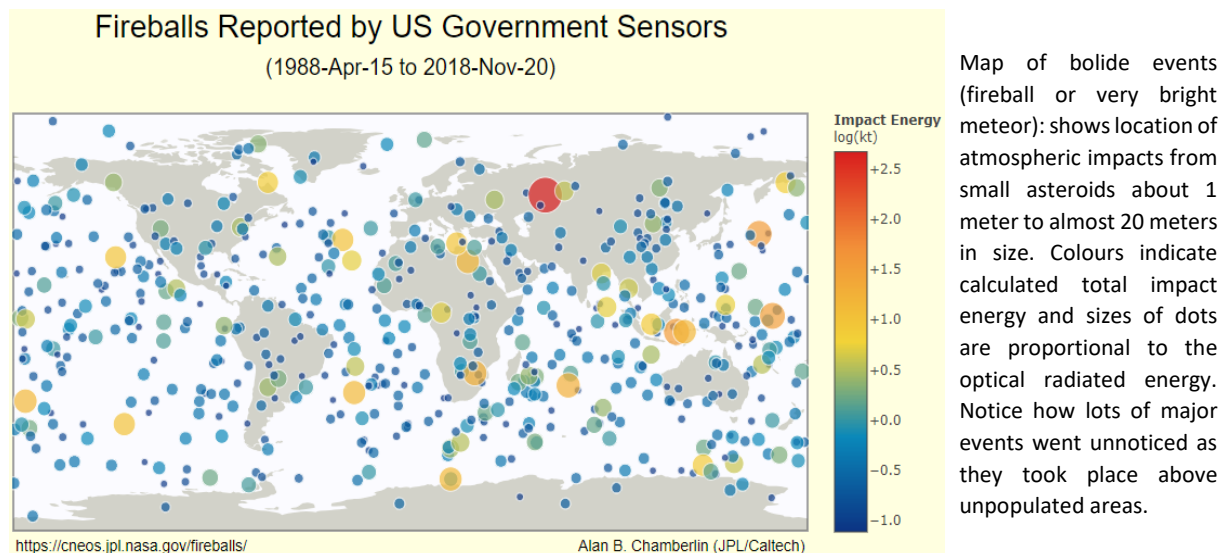
² ESA, "Asteroids: structure and composition of asteroids", www.esa.int/Our_Activities/Space_Science/Asteroids_Structure_and_composition_of_asteroids, retrieved: 28 January 2019.

³ Cosmos, Near Earth Asteroids, <http://astronomy.swin.edu.au/cosmos/N/Near+Earth+Asteroids>, retrieved: 28 December 2018.

2. Potentially hazardous asteroids

The ultimate fate of NEAs may be a collision with one of the terrestrial planets. In particular, asteroids that actually cross Earth's orbital path are known as Earth-crossers (Apollos and Atens). If they are large enough and if they could come dangerously close to Earth, these are classified as potentially hazardous asteroids (PHAs). More specifically, all asteroids with an Earth Minimum Orbit Intersection Distance of 0.05 AU (roughly 7,480,000 km) or less and with a minimum diameter of 140 m are considered PHAs.⁴ More than 10% (well over a thousand) of the total amount of NEAs are PHAs (mostly Apollos) and over a hundred of these have a diameter of more than 1 km.⁵

The amount of craters on the surface of the Moon, immediately shows that many objects have struck this body in the past. The same can be said for Earth, although it has less visible craters from impacts due to its protective atmosphere in combination with tectonic activity and erosion processes. Each day multiple meteoroids, stone-like or metal-like debris often coming from the asteroid belt, hit Earth. These are mostly meteors, which are too small to reach the surface. However, each year several are big enough to survive the passage through the atmosphere and become meteorites.



One widely accepted theory blames the impact 65 million years ago of an asteroid or comet at least 10 km in diameter for mass extinctions among many lifeforms, including the dinosaurs. More recently, in 1908, a NEA of 100 m in diameter exploded over a remote region in Siberia, killing wildlife within 30 km of the impact and causing forest fires that burned for weeks. In 1989 a much bigger NEA of 400 m wide came within 640,000 km of our planet. The Earth and the asteroid had passed the same point in space just 6 hours apart. Numerous lists of such near misses exist. Moreover, the last major impact took place only a few years ago in 2013. A NEA, known as the Chelyabinsk meteor, entered the atmosphere over Russia. The impact came as a complete surprise, since it was a 20 m sized undetected NEA. Luckily, due to its shallow angle, it exploded at a height of about 30 km and most of the energy was absorbed by the atmosphere. Although it caused a lot of material damage and injured over a thousand persons, no one was killed. However, the total kinetic energy before atmospheric impact has been estimated to be the equivalent of about 30 times the energy released by the atomic bomb detonated at

⁴ CNEOS, NEO Basics, https://cneos.jpl.nasa.gov/about/neo_groups.html, retrieved: 28 December 2018.

⁵ Cosmos, Near Earth Asteroids, <http://astronomy.swin.edu.au/cosmos/N/Near+Earth+Asteroids>, retrieved: 28 December 2018.

Hiroshima. The result could have been devastating if the meteor had a more extreme angle. The number of incidents and near misses in the past leave no doubt that Earth will encounter more of these objects in the future.

2.1 Remote sensing from Earth

First of all, observing the Moon for lunar impacts allows for a better understanding of how many Near-Earth Objects there are in proximity of the Earth. An ESA project called Near-Earth Object Lunar Impacts and Optical TrAnsients (NEOLITA)⁶ uses a large telescope to watch Moon flashes. These brief flashes are actually tiny rocks smashing into the surface. Since the Moon has no protective atmosphere, these are quite common and occur every few hours. Moreover, the presence of water on the Moon may also be explained by lunar impacts of asteroids containing water.

Furthermore, several monitoring programmes have been established to predict PHA impacts from Earth. Sentry for example, is a highly automated impact prediction system operated by the Jet Propulsion Laboratory Center for NEO Studies (CNEOS).⁷ It continually scans the most current asteroid catalogue for possibilities of future impact with Earth over the next 100 years. As illustrated by the Chelyabinsk meteor, not every single PHA has been detected. The monitoring programme primarily focusses on objects larger than 140 m. Those larger than 1 km should by now be discovered for 90% (around 900).⁸ It should be noted that this programme relies on Earth-based remote sensing, which means that diameters cannot be determined exactly. Moreover, asteroids typically have irregular shapes. Therefore a mean diameter, the diameter of a sphere that is in some manner equal to the asteroid, is used. It is based on density measures, for volume-equivalent, and on the albedo for surface equivalent. Calculations based upon an asteroids albedo are not fully accurate because these are estimated from measurements of an apparent magnitude at various times, at various distances from the Sun and Earth and at various phase angles. Moreover, since the actual shape of the asteroid is usually unknown, it is simply assumed to be spherical. Also, not all potential hazardous objects (PHO) on the list are asteroids. Therefore, the term Near Earth Objects (NEOs) is often used instead, as some of them are thought to be the nuclei of extinct comets or other objects rather than exclusively asteroids. It is even assumed that some objects could be man-made. An example of such an extraordinary case is 2000 SG344. Because of its very Earth-like orbit and because it would have been near the Earth at the time of the Apollo program, the possibility exists that it is a booster stage from a Saturn V rocket of Apollo 12 instead of an asteroid.

Numerous other efforts also catalogue NEOs with Earth based telescopes. These include for example the Minor Planet Center, the Lincoln Near-Earth Asteroid Research (LINEAR) and Spacewatch, but many more exist.

Some programmes specifically focus on alarming and evacuation systems. Examples are the Asteroid Terrestrial-impact Last Alert System by NASA and NEOShield by the European Union. Also, to raise

⁶ ESA, The mystery of the lunar lights, 2019, www.esa.int/kids/en/news/The_mystery_of_the_lunar_lights?fbclid=IwAR2kUbm3LwmFHwNjkYQKw0XOr8hhKcly3O9X1h3gdBaV8v_aBQ6aY53vtlo, retrieved: 28 January 2019.

⁷ CNEOS, Sentry: Earth Impact Monitoring, <https://cneos.jpl.nasa.gov/sentry/intro.html>, retrieved: 29 December 2018.

⁸ CNEOS? "Discovery statistics", <https://cneos.jpl.nasa.gov/stats/totals.html>

public awareness of the threat of an asteroid impact and how we can protect ourselves against it, each year, on the 30th of June, a dedicated Asteroid Day takes place.

2.2 Missions in space

Although most cataloguing of PHOs can be done with telescopes on Earth, space telescopes can pick out objects that are sometimes impossible to see from Earth. For example, the Wide-field Infrared Survey Explorer (WISE) was an infrared space telescope in Earth orbit which used its remaining capability, during a four-month mission extension called NEOWISE, to search for NEOs. The Hubble Space Telescope has also been used to image the surfaces of Ceres (950 km) and Vesta (525 km), the two largest asteroids in the main belt. ESA's Gaia satellite also aims to identify previously unknown asteroids and will enable a complete characterisation of the asteroid belt to improve our understanding of the origin and the evolution of the Solar System.⁹ Other space telescopes, such as NEOCam¹⁰, specifically designed to detect PHOs, are also planned or proposed for the near future.

Moreover some mission concepts focus on preventing a collision by deflecting a PHO from its orbit so that it passes the Earth instead of impacting it. Several collision avoidance techniques have been suggested. According to the NEOShield-2 programme, for large objects or objects with a short warning time, a blast deflection of some kind will be required. A kinetic impactor to change the course of a PHO could also be employed. If there would be enough warning time, a gravity tractor, pulling a PHO and slowly adapting its orbit over a long period, would be possible.¹¹ Another major initiative in this regard is the Asteroid Impact & Deflection Assessment Mission (AIDA) between NASA and ESA.¹² This full-scale planetary defence demonstration mission includes an asteroid impactor provided by NASA (DART) and possibly an asteroid rendezvous spacecraft by ESA (Hera). These will be sent to the binary asteroid 65803 Didymos. The DART probe will approach the binary system and crash into the asteroid moon at about 6 km/s. Hera will not be able to observe the impact itself (however, the Italian space agency ASI might fly a cubesat "SelfieSat"¹³ with DART that could observe the impact as it flies by), but it will characterize the consequences of the DART's impact on Didymos and its moon afterwards. Deflecting an asteroid's trajectory is a fundamental part of the energy transfer dynamics and has been under scientific debate for over a decade. The results will allow laboratory impact models to be calibrated on a large-scale basis, to fully understand how an asteroid would react to this kind of energy. In addition, it would mark the first time that humanity altered the dynamics of a Solar System body in a measurable way. The results should provide a baseline for planning any future planetary defence strategies, offering insight into the kind of force needed to shift the orbit of any incoming asteroid and how the technique could be applied if a real threat were to occur. Lastly, an alternative option would be to approach a PHO and intercept it. A specific mission that has been proposed in this regard was the

⁹ ESA, GAIA turns its eyes to asteroid hunting, <http://sci.esa.int/gaia/58706-gaia-turns-its-eyes-to-asteroid-hunting/>, retrieved 31 December 2018.

¹⁰ JPL, The Near-Earth Object Camera, <https://neocam.ipac.caltech.edu/>, retrieved: 29 December 2018.

¹¹ NEOShield-2, Mitigation Measures, www.neoshield.eu/mitigation-measures-kinetic-impactor-gravity/, retrieved: 29 December 2018.

¹² ESA, The Asteroid Impact & Deflection Assessment Mission, www.esa.int/Our_Activities/Space_Engineering_Technology/Hera/Asteroid_Impact_Deflection_Assessment_mission, retrieved: 29 December 2018.

¹³ SpaceNews, ESA plans second attempt at planetary defense mission, 2018, <https://spacenews.com/esa-plans-second-attempt-at-planetary-defense-mission/>, retrieved: 29 January 2019.

Asteroid Redirect Mission (ARM). It planned to demonstrate a planetary defence technique by capturing a boulder of a NEA with robotic arms and transporting it to a stable lunar orbit. However, the proposed 2018 NASA budget called for its cancellation.

Apart from these planetary defence proposals, there have already been missions to PHOs undertaking actual activities similar to such avoidance techniques. For example, in 2005 the Deep Impact spacecraft released a small impactor into a comet.¹⁴ However, this was merely done to study the interior composition of the comet. In the next chapter, passed and current science missions to NEAs will be discussed.

¹⁴ JPL, Deep Impact, www.jpl.nasa.gov/missions/deep-impact/, retrieved: 29 December 2018.

3. Exploration missions to NEAs

Mass extinction threats aside, asteroids also offer two great opportunities. The first will be discussed in this chapter and is about the information that these space rocks hold of the history of planets, the Sun and even on evolution of life on Earth.¹⁵ Theories suggest that the chemical building blocks of life and much of Earth's water arrived on asteroids or comets that bombarded the planet in its youth. As opposed to the matter comprising large bodies such as the planets and the Moon, changing over time due to thermal processes, asteroids are believed to be small enough to have preserved the state of the early solar system and are sometimes referred to as celestial fossils. A soil sample from an asteroid can give us clues about the raw materials that made up planets and asteroids in their formative years. However small the sample amount may be, its scientific significance can be tremendous. Exploration missions to NEAs provide close range imagery, detailed data and samples which also help to improve the analysis of remote sensing observations and meteorite collections.

To keep things brief, and in order to stay on topic, the missions described in this chapter are all linked to asteroids. Missions to comets, though similar bodies and potential PHOs too, fall outside the scope of this paper. However, some missions which were not specifically designed to study NEAs still performed an asteroid flyby. These will be highlighted first, thereafter missions with a main focus on NEAs will be discussed. The other opportunity, focussing on the presence of natural resources in asteroids with regard to commercial interests, will be described in the next and final chapter.

3.1 Asteroid flybys

NASA's Galileo mission was launched in 1989, lasting until 2003.¹⁶ It aimed to study Jupiter and its moons. On its way to Jupiter, it became the first spacecraft to visit an asteroid. In fact, the spacecraft performed not just one flyby but also a second. The first was of 951 Gaspra in 1991. The other flyby, 2 years later around a second asteroid, 243 Ida, discovered the first asteroid moon, Dactyl.



Galileo image of 243 Ida and its moon Dactyl on the right

Launched in 2004, Rosetta was an ESA mission to perform a detailed study of a comet.¹⁷ During its journey, the spacecraft flew by the asteroids 21 Lutetia and 2867 Šteins. The Rosetta probe passed Lutetia in 2010. It was the largest asteroid (approximately 100 km in diameter) visited by a spacecraft until Dawn arrived at Vesta in 2011.

¹⁵ NASA, "What is an asteroid?", www.spaceplace.nasa.gov/asteroid/en/, retrieved: 27 December 2018.

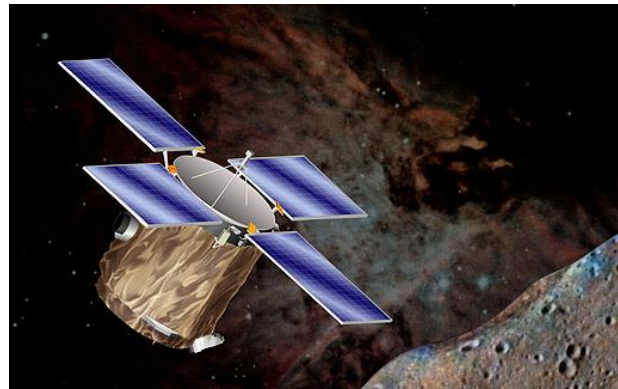
¹⁶ JPL, Galileo Mission, www.jpl.nasa.gov/missions/galileo/, retrieved: 30 December 2018.

¹⁷ ESA, Europe's Comet Chaser, www.esa.int/Our_Activities/Space_Science/Rosetta/Europe_s_comet_chaser, retrieved: 31 December 2018.

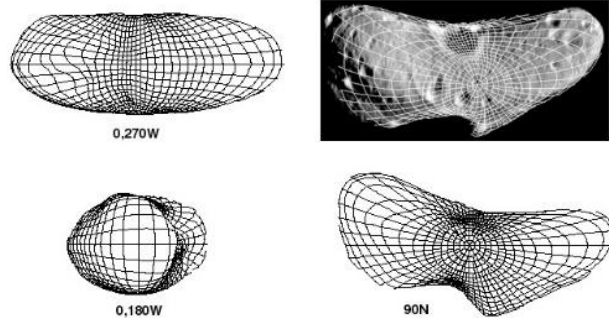
Dawn was launched by NASA in 2007 with the goal to study protoplanet Vesta and dwarf planet Ceres of the asteroid belt.¹⁸ After exhausting all of its fuel, the mission retired on 1 November 2018. It is currently in an uncontrolled orbit around its second target, the dwarf planet Ceres. It is the first mission to orbit an object in the main asteroid belt, the first to visit a dwarf planet and the first to orbit two targets.

3.2 NEAR Shoemaker

Launched in 1996, the Near Earth Asteroid Rendezvous (NEAR) was the first-ever to orbit an asteroid and to touchdown on the surface of an asteroid.¹⁹ On its way it also performed a 25-minute flyby of 253 Mathilde, a C-Type asteroid with a 52 km mean diameter located in the asteroid belt. Images of the surface and craters revealed that asteroids such as Mathilde are made of the same dark, black rock throughout and seems to confirm that C-type asteroids are pristine samples of the primitive building blocks of the larger planets. The spacecraft's final purpose was to study the NEA 433 Eros from close orbit over a period of a year. 433 Eros is the second largest NEA (after 1036 Ganymed) with a mean diameter of 16,8 km. It is an S-type of the Amor group. The mission ended with a touchdown on 12 February 2001. Although NEAR was not designed as a lander, it survived the descent due to the low-velocity, low-gravity impact and became the first spacecraft to touchdown on an asteroid. After the impact, the spacecraft continued to signal using the omnidirectional low-gain antenna. In this final stage, the gathered data provided additional information about the composition of Eros and of the gamma-ray spectrum from the surface. The final contact was made on 28 February.



Artist impression of the NEAR Shoemaker spacecraft



An accurate model of Eros' shape helps to determine the asteroid's key properties. The total space enclosed by the surface of the shape model represents the asteroid's estimated volume. The asteroid's mass (determined using NEAR Shoemaker's radio tracking) is divided by its volume to estimate its density (valuable for understanding what kind of rock makes up the interior) The shape also provides information about the distribution of mass below the surface.

Image: 2000 Science Magazine

¹⁸ NASA, Dawn Mission Overview, www.nasa.gov/mission_pages/dawn/mission/index.html, retrieved: 31 December 2018.

¹⁹ NASA, NEAR Shoemaker, <https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=1996-008A>, retrieved: 30 December 2018.

3.3 Hayabusa (MUSES-C) & Hayabusa2

Hayabusa (MUSES-C) was launched in 2003 and was originally designed as a technology demonstration mission.²⁰ It carried a mini-lander (MINERVA), but this failed to reach the surface. However, in 2005 the Hayabusa spacecraft landed on the surface of 25143 Itokawa, a PHA S-type from the Apollo group with a mean diameter of approximately 300 m. After the above mentioned touchdown of NEAR, it was only the second time in history that a spacecraft descended to the surface of an asteroid and the first mission to return a sample of material from the surface of an asteroid. It gathered new findings about the PHA, including its gravity and surface conditions. The mission was finalised in 2010 when the 40-centimeter-wide capsule was delivered in South Australia, where ground teams could recover it. The returned samples bridge the gap between ground observation data of asteroids and the matching of laboratory analysis of meteorite collections. For example, the hypothesis that ordinary chondrites (the most common meteorites on Earth) originate from S-type asteroids, was confirmed through the exploration of Itokawa.



Artist impression of the Hayabusa spacecraft at Itokawa

Next, in 2014, the successor mission Hayabusa2 was launched. Target of this mission is 162173 Ryugu.²¹ This is a 900 m PHA and is a C-type in the Apollo group. C-type asteroids are more primordial bodies than S-type asteroids and are considered to preserve the most pristine materials in the Solar System: a mixture of minerals, ice and organic compounds. By analysing samples acquired from this C-type asteroid, more knowledge will be gathered about the origin and evolution of the inner planets, and in particular the origin of water and organic compounds on Earth. All relevant to the origin of life itself.



Image captured immediately before a hop of Rover-1B
on 23 September 2018
Credits: JAXA

Hayabusa2 carries four small landers to investigate the asteroid surface. On 21 September 2018, two small rovers (Rover-1A HIBOU and Rover-1B OWL), each weighing just over 1 kg, were deployed. They moved by hopping in the low gravitational field, using a torque generated by rotating masses within. These were the first-ever rovers to be deployed on an asteroid. The Mobile Asteroid Surface Scout (MASCOT) was next in line to make a successful descent. It is the biggest lander, weighing almost 10 kg. This shoebox sized and shaped device is capable of tumbling once to reposition itself for further measurements. It also

²⁰ JAXA, Asteroid Explorer "HAYABUSA" (MUSES-C), http://global.jaxa.jp/projects/sat/muses_c/, retrieved: 31 December 2018.

²¹ JAXA, Asteroid Explorer "Hayabusa2", <http://global.jaxa.jp/projects/sat/hayabusa2/>, retrieved: 31 December 2018.

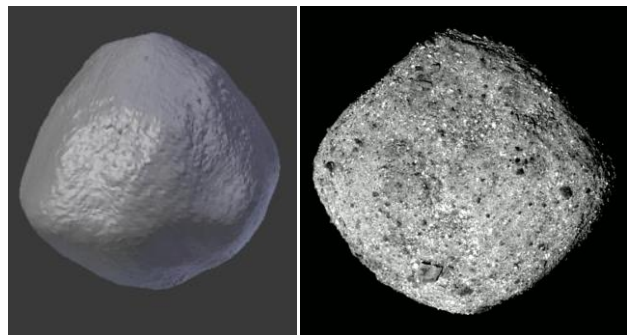
serves as a scouting vehicle for assessing candidate sampling sites. The remaining ROVER-2, another small rover weighing about 1 kg, will make a landing in July 2019. The data collected from these landers includes in-situ study of the surface composition, properties, temperature and imagery. All landers will attempt manoeuvres across the asteroid's surface to take measurements at different locations.

Moreover, three samples will be collected by the spacecraft itself. The minimum desired amount per sampling is 0.1 g, but the system has capacity to collect up to 10 g per sample. Apart from surface regolith, another sample is desired of material from under the asteroid's surface which will be exposed by a kinetic impactor, shot from a distance. The mission will be finalised with the sample return in 2020.

3.4 OSIRIS-Rex

OSIRIS-REx was launched in 2016 as NASA's first asteroid sample return mission. Its target is the NEA Bennu, a 500 m C-type asteroid in the Apollo group. The main goal of the mission is to obtain a sample of at least 60 g. As planned, the spacecraft reached Bennu in December 2018. Returning the sample to Earth is planned for 2023. Just like the Hayabusa missions, the sample will deliver new information about the history and evolution of our solar system. Collected data already showed interesting results.²²

The OSIRIS-REx Camera Suite (OCAMS) confirmed the original model of Bennu's shape which relied on ground-based telescopic observations of Bennu. That model closely predicted the asteroid's actual shape, diameter, rotation rate, inclination and overall shape. The shape of Bennu deserves some attention, since it belongs to the spinning top asteroid class, which has been seen repeatedly in recent years. A similar shape was for instance observed by the Rosetta flyby of asteroid Šteins and by Hayabusa2 of Ryugu. The typical diamond shape is due to the asteroid's rapid spin and the resulting centrifugal force thereof, moving material away from the poles, causing a bulge around its equator.



3D model of Bennu (2016)

Image taken by the OSIRIS-Rex spacecraft showing Bennu from a distance of around 80 km (2018)

Credits: NASA's Goddard Space Flight Center/University of Arizona

A possible explanation for the spin is the so-called Yarkovsky–O'Keefe–Radzievskii–Paddack effect (YORP) effect. This implies that asteroids re-radiate energy as heat by the warming of sunlight, which gives rise to a tiny amount of thrust. Eventually Newton's Third Law, every action has an equal and opposite reaction, exerts itself. Due to their irregular shapes, some parts of asteroids generate more thrust than others, leading to a turning force. The resulting centrifugal force could continue to the

²² NASA, "NASA's Newly Arrived OSIRIS-REx Spacecraft Already Discovers Water on Asteroid", 2018, www.nasa.gov/press-release/nasa-s-newly-arrived-osiris-rex-spacecraft-already-discovers-water-on-asteroid, retrieved: 16 January 2019.

point that material is actually thrown out into space, leading to the creation of a binary or multiple asteroid system. Some might also crumble apart altogether. For larger asteroids, YORP is less likely to influence shape, as their ratio between mass and surface area is much higher.²³

The model of Bennu thus closely predicted its shape, but the surface appears to be much more rough, as the quantity of boulders on it is higher than expected. Furthermore, the mission has revealed that Bennu contains water-bearing clay minerals. While Bennu itself is too small to have ever hosted liquid water, the finding does indicate that liquid water was present at some time on Bennu's parent body, a much larger asteroid.

Bennu is also a PHA.²⁴ As described in chapter 2, multiple planetary defence initiatives collect as much information as possible about forces that influence the movement of asteroids in order to detect and catalogue PHAs. By determining Bennu's precise position in the solar system and its exact orbital path, combined with existing, ground-based observations, the space measurements will help clarify how its orbit is changing over time. The mission is therefore also useful for asteroid impact avoidance purposes.

²³ ESA, Spinning-top asteroids from Rosetta to Hayabusa2 and maybe Hera, www.esa.int/Our_Activities/Space_Engineering_Technology/Hera/Spinning-top_asteroids_from_Rosetta_to_Hayabusa2_and_maybe_Hera, retrieved: 29 January 2019.

²⁴ NASA, "Planetary Defense: The Bennu Experiment", 2018, www.nasa.gov/feature/planetary-defense-the-bennu-experiment, retrieved: 16 January 2019.

4. NEA mining

Finally, since they contain lots of valuable natural resources, asteroids have become subject to specific space mining plans as well. Even on Earth's surface, one of the world's major mining communities originates from a giant impact crater called the Sudbury Basin in Canada, where a 10-15 km object struck the Earth some 1.8 billion years ago. The large impact crater filled with magma containing nickel, copper, platinum, palladium, gold and other metals, which is why it is an excellent mine site today. The Earth's crust has relatively low concentrations of these metals, since they are mostly contained inward to the planet's core. However, some types of asteroids typically have a higher concentration of these elements. It is speculated that these asteroids could be mined to exploit these raw materials. Apart from minerals and metals, some asteroids also contain water which could be even more useful for human presence in space.

Lots of possibilities have been proposed for such activities. From in-situ utilisation to the dropping onto Earth's surface of an asteroid weighing several hundred tonnes. With regard to PHAs, it is often claimed that instead of a potential threat to Earth, these objects can be transformed into usable resources.²⁵ However, bringing asteroids towards Earth appears to be a reckless activity risking the opposite. In any case, this chapter will be limited to asteroid mining activities according to a proposed mission of Planetary Resources.

4.1 Arkyd-301

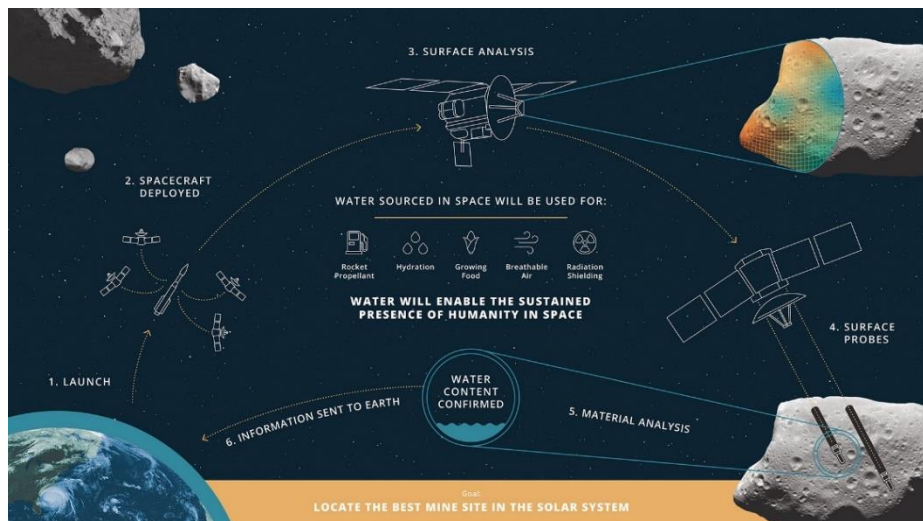
ARKYD Astronautics was founded in 2009 in the United States. In 2012, the company was reorganised and renamed to Planetary Resources. It is one of the select few companies to work on asteroid mining. The ultimate aim of the company is to become the leading provider of resources and products in deep space by identifying, extracting and refining resources from NEA. The reason why NEAs are an interesting mining objective is twofold. First of all, being near-Earth, they offer realistic accessibility. The other main reason is of course all about their natural resources potential. Asteroids contain the resources that make it possible to fuel and sustain life in space, creating a new paradigm of travel and human presence in space. Especially the availability of water draws the company's main attention. Water can be used to sustain life support functions and can as well be refined into propellant for spacecraft. Actual mining activities in space have however not yet been realised. Legal, technical and economic barriers are still very challenging. Planetary Resources has however taken important steps for a potential future asteroid mining industry. For example, it successfully lobbied towards the passage of national space legislation in the United States and even in Luxembourg, through a partnership to encourage the commercial exploration and utilization of space-based resources.²⁶

The first stage of the company's strategic plan includes the testing of their technologies in Low Earth orbit (LEO) with small satellite missions. This has been realised with 2 CubeSats, in 2015 with Arkyd-3 and in 2018 with Arkyd-6. These missions are limited to technology demonstration activities, designed

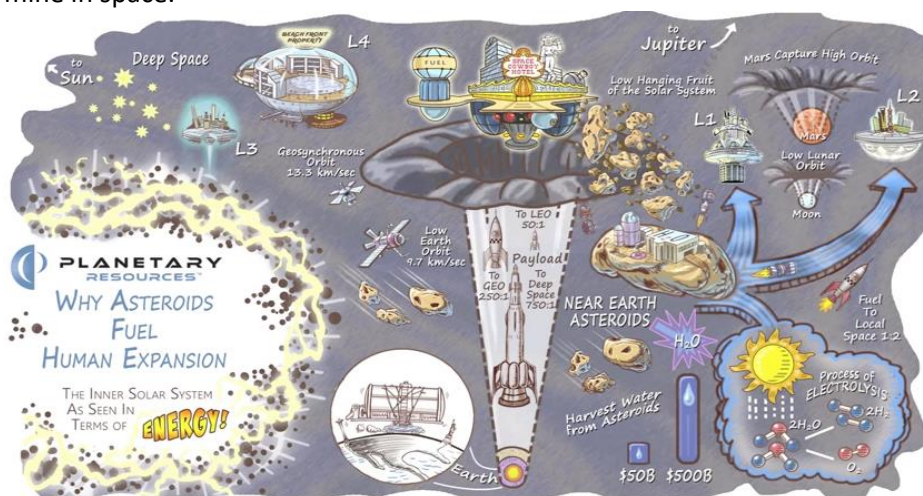
²⁵ N. GOSWAMI, "China's Get-Rich Space Program", *The Diplomat*, 2019, <https://thediplomat.com/2019/02/chinas-get-rich-space-program/>.

²⁶ Space Resource Exploration and Utilization Act, H.R. 2262, 25 november 2015, www.congress.gov/bills/114/congress/house-bill/2262/text; Law on the Exploration and Use of Space Resources, No. 674, 28 July 2017, <http://legilux.public.lu/eli/etat/leg/loi/2017/07/20/a674/jo>.

to detect water resources in space through Earth-observation with infrared instrumentation. The ultimate goal is to use this technique to characterise hydrated resources on NEAs. The next step would mean to use LEO based space telescopes to study asteroids, or to immediately send probes to asteroids, surveying and exploiting the resources.²⁷ Through an extensive multi-year observational prospecting program, Planetary Resources has selected the most promising, water-rich asteroid targets for the company's first exploration mission. Arkyd-301 is the company's next spacecraft platform, that should be capable of detecting water on NEAs, which will be the beginning of a commercial deep space exploration program.



The purpose of this commercial deep space exploration program is to identify and unlock the critical water resources necessary for human expansion in space. The initial mission will identify the asteroids that contain the best source of water, and will simultaneously provide the vital information needed to build a commercial mine which will harvest water for use in space. The program is an extensive data-gathering series of missions in deep space that will visit different NEAs. Multiple spacecraft, using low-thrust ion propulsion systems, will visit a pre-determined target asteroid to collect data and test material samples. Data collection will include hydration mapping and subsurface extraction demonstrations to determine the quantity of water and the value of the resources available. The information gathered could allow Planetary Resources to design, construct and deploy the first commercial mine in space.



²⁷ www.planetaryresources.com/company/timeline/, retrieved: 26 December 2018.

Conclusion

At first sight, asteroids give a rather dull impression. However, throughout the different chapters of this paper, it appears that these rocky remnants contain more than one would expect. First of all, the dangers of PHAs for humankind as a whole should not be overlooked. These floating rocks, lurking in the darkness in close proximity to our planet, are therefore monitored as much as possible. This is done by different catalogues in coordination with remote sensing missions from Earth and space. Moreover, multiple initiatives exist in order to develop planetary defence techniques.

Impact disasters aside, NEAs also offer two great opportunities. As leftovers from the formation of the Solar System, asteroids carry a lot of information about the conditions in the dust cloud that surrounded the Sun when the planets were born. Asteroids are believed to be small enough to have preserved the state of the early solar system. A soil sample from these celestial fossils can give us clues about the raw materials that made up planets, including our own, in their formative years. However small the sample amount may be, its scientific significance can be tremendous. The gathered data by exploration missions to NEAs also help to refine the analysis of remote sensing observations and meteorite collections.

Finally, by their accessibility and rich compositions, NEAs increasingly draw substantial commercial interests. One illustration was provided in the last chapter. The priority of Planetary Resources to extract water in order to boost human presence and exploration in deep space seems like a noble purpose and could initiate a new kind of space civilisation.

Bibliography

CNEOS, NEO Basics, https://cneos.jpl.nasa.gov/about/neo_groups.html, retrieved: 28 December 2018.

CNEOS, Sentry: Earth Impact Monitoring, <https://cneos.jpl.nasa.gov/sentry/intro.html>, retrieved: 29 December 2018.

Cosmos, Near Earth Asteroids, <http://astronomy.swin.edu.au/cosmos/N/Near+Earth+Asteroids>, 28 December 2018.

ESA, The Asteroid Impact & Deflection Assessment Mission, www.esa.int/Our_Activities/Space_Engineering_Technology/Hera/Asteroid_Impact_Deflection_Assessment_mission, 29 December 2018.

ESA, GAIA turns its eyes to asteroid hunting, <http://sci.esa.int/gaia/58706-gaia-turns-its-eyes-to-asteroid-hunting/>, retrieved 31 December 2018.

ESA, Europe's Comet Chaser, www.esa.int/Our_Activities/Space_Science/Rosetta/Europe_s_comet_chaser, retrieved: 31 December 2018.

ESA, "Asteroids: structure and composition of asteroids", www.esa.int/Our_Activities/Space_Science/Asteroids_Structure_and_composition_of_asteroids, retrieved: 28 January 2019.

ESA, The mystery of the lunar lights, 2019, www.esa.int/kids/en/news/The_mystery_of_the_lunar_lights?fbclid=IwAR2kUbm3LwmFHwNjkYQKw0XOr8hhKcly3O9X1h3gdBaV8v_aBQ6aY53vtIo, retrieved: 28 January 2019.

ESA, Spinning-top asteroids from Rosetta to Hayabusa2 and maybe Hera, www.esa.int/Our_Activities/Space_Engineering_Technology/Hera/Spinning-top_asteroids_from_Rosetta_to_Hayabusa2_and_maybe_Hera, retrieved: 29 January 2019.

NASA Science, Solar System Exploration, <https://solarsystem.nasa.gov/asteroids-comets-and-meteors/asteroids/in-depth/>, retrieved: 27 December 2018.

NASA, "What is an asteroid?", www.spaceplace.nasa.gov/asteroid/en/, retrieved: 27 December 2018.

NASA, NEAR Shoemaker, <https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=1996-008A>, retrieved: 30 December 2018.

NASA, Dawn Mission Overview, www.nasa.gov/mission_pages/dawn/mission/index.html, retrieved: 31 December 2018.

NASA, "Planetary Defense: The Bennu Experiment", 2018, www.nasa.gov/feature/planetary-defense-the-bennu-experiment, retrieved: 16 January 2019.

NASA, "NASA's Newly Arrived OSIRIS-REx Spacecraft Already Discovers Water on Asteroid", 2018, www.nasa.gov/press-release/nasa-s-newly-arrived-osiris-rex-spacecraft-already-discovers-water-on-asteroid, retrieved: 16 January 2019.

NEOSShield-2, Mitigation Measures, www.neoshield.eu/mitigation-measures-kinetic-impactor-gravity/, retrieved: 29 December 2018.

JPL, The Near-Earth Object Camera, <https://neocam.ipac.caltech.edu/>, retrieved: 29 December 2018.

JPL, Deep Impact, www.jpl.nasa.gov/missions/deep-impact/, retrieved: 29 December 2018.

JPL, Galileo Mission, www.jpl.nasa.gov/missions/galileo/, retrieved: 30 December 2018.

JAXA, Asteroid Explorer "HAYABUSA" (MUSES-C), http://global.jaxa.jp/projects/sat/muses_c/, retrieved: 31 December 2018.

JAXA, Asteroid Explorer "Hayabusa2", <http://global.jaxa.jp/projects/sat/hayabusa2/>, retrieved: 31 December 2018.

Planetary Resources, www.planetaryresources.com/company/timeline/, retrieved: 26 December 2018.

SpaceNews, ESA plans second attempt at planetary defense mission, 2018, <https://spacenews.com/esa-plans-second-attempt-at-planetary-defense-mission/>, retrieved: 29 January 2019.

Legislation

Space Resource Exploration and Utilization Act, H.R. 2262, 25 november 2015, www.congress.gov/bill/114th-congress/house-bill/2262/text.

Law on the Exploration and Use of Space Resources, No. 674, 28 July 2017, <http://legilux.public.lu/eli/etat/leg/loi/2017/07/20/a674/jo>.