Active Asteroids

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Contents

1 Introduction

Asteroids and comets have been thought to be separate kinds of objects in our solar system. These two different classes did seem likely, considering the history of asteroid and comet observations. Comets with their splendid tails have been known for millennia, while dim and unassuming asteroids were first discovered barely two centuries ago.

Recently, evidence has been found that asteroids and comets might just be two end-members of a continuum of solar system objects. Several ordinary objects with typical asteroid orbits in the main asteroid belt have surprisingly displayed comet-like mass-loss activity.

Now, there must be a process that causes the ejection of dust particles from the asteroid, be it the same as for classical comets or something entirely different. As more active asteroids have been found, the number of possible activity-driving mechanisms has increased.

In this bachelor's thesis I will explore the topic of active asteroids. I will first describe the properties of classical asteroids and comets, and how the distinction between them has been made. I will then go through eight mass-loss mechanisms of active asteroids, tell about active asteroid observations, and review three examples of known active asteroids. Finally, I will talk about the future and possible upcoming missions of the active asteroid research.

Figure 1.1: Woodcut print of the Great Comet of 1577 by Jiri Daschitzsky. [1]

2 Asteroid or Comet?

Historically, asteroids and comets have been considered two separate classes of solar system objects. Based on different kinds of criteria, it has been possible to classify every object as either a comet or an asteroid. [2]

The differences of comets and asteroids can be simplified as follows. Comets are icy bodies ultimately originating from the outer solar system, that can become active and bright as they approach the Sun. They have been known for much longer than asteroids that are rocky, dim, and inert throughout their lifetimes in the inner solar system out to the orbit of Jupiter. [3]

The classical distinctions of asteroids and comets can generally be either observational, physical, dynamical, or evolutional [3]. One just has to choose the most convenient criteria to separate the object classes [2].

The observational distinction is perhaps the traditionally best-known one. It is usual to classify asteroids and comets based on their appearance in the sky; comets appear fuzzy, while asteroids do not. This means that observed comets typically emit mass and have comae and tails, while asteroids seem like sharp points of light. [4]

The distinction can also be made based on the physical composition of the body. Comets contain abundantly volatile materials, e. g. water ice. Asteroids are classically rocky, because it is difficult to preserve ices in the inner solar system, where the ice-rich comets usually start to sublimate. [3]

This brings us to the third, dynamical criterion. Many comets have highly eccentric orbits and spend most of their time far from the Sun. Typical asteroid orbits are more circular and they are located closer to the Sun. [3]

Lastly, if the distinction is made on evolutional grounds, asteroids have spent their lifetimes on stable orbits in the inner solar system. Comets come originally from the outer solar system. [3]

Some of these properties are tightly connected to each other. For example, an object that has formed in the inner solar system, that orbits on a circular asteroid-like orbit, and that does not contain any ice and therefore also does not display activity caused by sublimation, can be an asteroid according to each of the criteria.

However, there can also be an object that is on an eccentric, cometary orbit, but does not show any activity. Now, the question is, if this object is a dormant comet, i. e. a comet whose volatile ices have been covered with a layer of inactive material, or if it is an asteroid that has been kicked out of its previously stable main-belt orbit.

There is also a group of very interesting objects that in every other sense are asteroids, but they behave like comets showing mass-loss activity [3]. These bodies are called active asteroids and are the topic of this thesis.

In fact, many objects with characteristics of both asteroids and comets have been detected. In the light of these recent findings, the classical definitions of asteroids and comets are no longer entirely useful. It is nevertheless worth going through asteroids and comets as separate classes before getting into the spectrum of active asteroids. [3]

2.1 Asteroids

Asteroids have only been known for a little over two hundred years. The first asteroid of the main belt, 1 Ceres, was discovered in 1801. It was initially reported to be a comet or a star-like object on a planet-like orbit, since it looked like a sharp point of light that moved against the background of stars. Ceres was then thought to be a planet, before it was finally classified as an asteroid and a minor planet. [4]

Minor planets are non-cometary small bodies with radii ranging from a few metres to 1000 kilometres, and they orbit the Sun. Asteroids in our solar system are rocky minor planets. Most of them orbit the Sun in the main asteroid belt, which is located between the orbits of Mars and Jupiter, at distances of approximately 2.1 to 3.3 astronomical units (AU) from the Sun. [5]

In addition to the main belt asteroids, there are two asteroid populations in the inner solar system: near-Earth asteroids and Trojan asteroids. Near-Earth asteroids have perihelia closer than 1.3 AU to the Sun. Trojan asteroids orbit the Sun at Jupiter's distance, 5.2 AU, near Jupiter's triangular Lagrangian points. [5]

The origin of the main belt asteroids is believed to be in the inner solar system during the accretion of planets [4]. Asteroid orbits are stable and circular with low eccentricities [3].

In the restricted three-body problem, when a small body encounters a larger body, e. g. Jupiter, its orbital elements may change. The relation of the pre-encounter and post-encounter semi-major axis, eccentricity, and inclination of the small body can be described by the Tisserand parameter. The Tisserand parameters with respect to Jupiter are $T_J > 3$ for asteroids, which means that they are not coupled to Jupiter and do not cross the orbit of Jupiter. [2]

As they are constantly heated by the Sun, it is difficult for volatile material, such as water ice, to be preserved on asteroids. Thus, the composition of asteroids is generally solid, rocky, and non-volatile. Asteroids are traditionally considered inert, showing no mass-loss in the form of gas or dust flow. [3, 4] Most asteroids in the main belt are primitive carbonaceous type C, or more processed stony type S [5, 6].

Asteroids have radii smaller than 1000 kilometres. Their sizes are power-law distributed so that there are much more asteroids of smaller sizes and fewer of the big, near dwarf-planet-sized ones. For example, only four asteroids are larger than 400 kilometres in diameter, but millions of asteroids have radii smaller than one kilometre. [4]

The shapes of asteroid bodies are usually irregular, since they are too small to reach hydrostatic equilibrium and a spherical shape. Asteroids are also too small to have atmospheres that would protect their surfaces from cratering and fracturing due to collisions and radiation in space. Collisions have influenced the objects in the asteroid belt, and many asteroids are fragments of larger asteroids that have been shattered by collisions. Some asteroids are rubble piles, which consist of fragments loosely bound together by gravitation. [4]

Many asteroids belong to an asteroid family, a cluster of asteroids that share similar orbital elements, including semimajor axis, eccentricity, and inclination. The members of one family are usually also similar in composition, as they are remnants of one larger body that has disrupted collisionally. [4]

Figure 2.1 shows an example of an asteroid, (243) Ida, and its irregular shape. Ida also has numerous craters on its surface, which demonstrates the amount of collisions that can happen in the asteroid belt. Ida itself is approximately 32 kilometres in diameter [7] and also has a smaller moon called Dactyl [8]. Figure 2.3 shows near-Earth asteroid (101955) Bennu, whose surface looks much rougher than that of Ida.

2.2 Comets

An active comet with its tail can appear vast and bright in the sky, and be visible from Earth with naked eye. That is why comets are a class of small bodies that have been known for millennia. Earliest records of them date back to China 600 BCE. [5] Figure 1.1 shows a depiction of a comet from the 1500s [1].

Comets are icy bodies that activate when they approach the perihelion of their orbit, as the heat of the Sun causes sublimation of the volatile ices of the comet nucleus. The comet then forms a coma, and a tail of particles swept away. The tail and the coma give the comet a fuzzy look

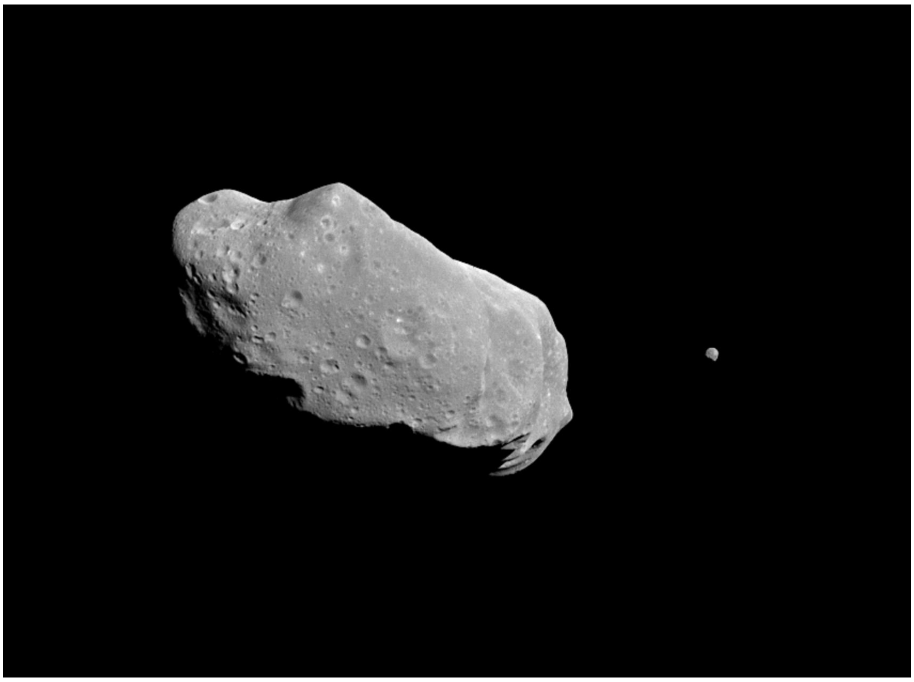

Figure 2.1: Asteroid (243) Ida and its moon Dactyl. Image credit: NASA/JPL. [9]

in the sky. [3] Figure 2.2 shows an example of an active comet, Hale-Bopp, with its coma and tail [10].

The nucleus of a comet is typically 1–50 kilometres in diameter and consists largely of volatile materials. It is surrounded by a cloud-like coma of gas and dust with a size of 10^4–10^5 kilometres. The hydrogen coma extends even farther than that. [5]

Solar radiation pressure causes the particles of the coma to be driven out. Thus, a yellowish dust tail is formed outward from the Sun, with a length up to 10^6–10^7 kilometres. Solar wind also has its effect on the comet and a bluish ion tail forms along the interplanetary magnetic field lines. [5] The difference between the yellow dust tail and blue ion tail can be clearly seen in Figure 2.2, which shows the dust tail spreading from left to right and the ion tail stretching towards the upper right corner of the image. [10]

The orbits of comets are usually highly eccentric, ranging from perihelia in the inner solar system to aphelia in the outer solar system. A comet spends most of its time frozen, far from the heat of the Sun, and that is how comets have managed to preserve their volatile materials longer than asteroids. A comet only becomes active and mass-losing if it is heated sufficiently by the Sun near the perihelion of its orbit in the inner solar system. [3]

Figure 2.2: Comet C/1995 O1 Hale-Bopp, on March 14 in year 1997, displaying a yellowish dust tail and a bluish ion tail. Image credit: ESO/E. Slawik. [10]

The origins of comets lie in the outer solar system, beyond Neptune's orbit. Short-period comets, or returning comets, are from the Kuiper belt, and long-period, or dynamically new ones, stem from the Oort cloud. [6]

Comets have a wide variety of different orbits in the solar system. They can be grouped based on their Tisserand parameter T_J and semi-major axis a. Comets with $T_J < 2$ are called 'nearly isotropic' and comets with $T_J > 2$ 'ecliptic', due to the inclinations of their orbits. [11]

Nearly isotropic comets consist of 'new' comets with semi-major axes $a > 10\,000\,\mathrm{AU}$ and 'returning' comets with $a < 10\,000\,\mathrm{AU}$. Returning comets can be further divided into 'Halley family' comets with $a < 40\,\mathrm{AU}$, which are in resonances with a planet, e. g. Jupiter, and 'external' comets with $a > 40\,\mathrm{AU}$. [11]

Ecliptic comets that have $T_J < 3$ and can cross Jupiter's orbit are 'Jupiter family' comets. There are also two classes with $T_J > 3$ unable to cross the orbit of Jupiter: the 'Encke type' inside Jupiter's orbit and the 'Chiron type' outside of it. [11] 'Main belt comets' also have $T_J > 3$, and their inactive counterparts are asteroids [2].

When a comet has lost all its near-surface ice due to having been heated repeatedly at perihelion, it becomes dormant or even extinct. Now the comet, albeit still on a comet-like orbit, has basically become an asteroid. [5]

2.3 Active Asteroids and Main-Belt Comets

As mentioned before, there are many objects in the solar system that share properties with both asteroids and comets. The entire population exhibiting a range of observational, dynamical, and physical asteroid or comet characteristics can be called 'asteroid-comet continuum objects'. [12]

This continuum consists of minor planets and classical comets, but also extinct and dormant comets, as well as active asteroids, which include main belt comets and disrupted asteroids. Many other object classes, for example parent bodies of meteor streams, also belong to the continuum. [12]

Any objects on asteroidal orbits showing observationally comet-like behaviour can be referred to as 'active asteroids', regardless of the mechanism of mass-loss [13]. An even more general term would be 'active main-belt objects', or AMBOs [12].

'Main belt comets', or MBCs, are icy small bodies on asteroidal orbits, that periodically lose mass by sublimation of ices, very much like classical comets do [5]. Main belt comets are a relatively new class of continuum objects, established in 2006, ten years after the observation of the first main belt comet, 133P/Elst-Pizarro [13].

Main belt comets do not originate in the Kuiper belt or the Oort cloud like classical comets, but have formed in the inner solar system and spent their time in the main asteroid belt. Despite being so close to the Sun, they have managed to preserve volatile materials underneath a regolith layer. [5]

The term 'main belt comet' does not cover all of the known active objects with orbits in the asteroid belt. Some years after the recognition of the new class, other kinds of disrupted asteroids were discovered. The reason for disrupted asteroids to exhibit activity is some kind of physical disruption, e. g. impact or rotational instability. [13]

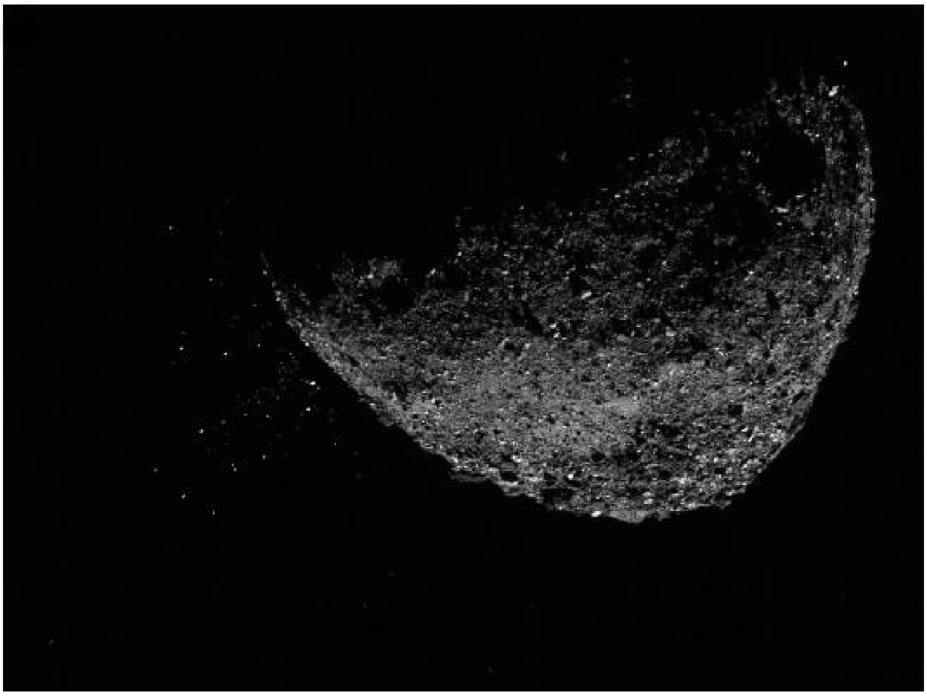

Figure 2.3: Asteroid (101955) Bennu ejecting particles imaged by NASA's OSIRIS-REx mission in 2019. Bennu's surface is rough and covered in boulders, rocks, and regolith. Image credit: NASA/Goddard/University of Arizona/Lockheed Martin. [14]

The activity-causing dust-ejection mechanism cannot always be defined simply as either sublimation or disruption. For example, an impact on an asteroid could eject particles from the surface but also expose ice that could then begin to sublimate. [13] In this case, neither of the names 'main belt comet' or 'disrupted asteroid' would perfectly apply, but the more comprehensive term 'active asteroid' would be the best.

For some asteroids, there is not enough evidence to say which mechanism is responsible for the activation, and it is very useful to just call them 'active asteroids'. There are also active asteroids that are not exactly in the main belt, e. g. some near-Earth objects, that could not be called 'main-belt comets'. [2]

3 Mass-Loss Mechanisms of Active Asteroids

There are several drivers of mass loss that can be the cause of the observable activity of an asteroid. After noticing an active asteroid, the next step is to find out what kind of a mechanism is responsible for the shedding of its mass. The possible mechanisms of mass loss include sublimation, rotational instability, impact ejection, electrostatic repulsion, radiation pressure sweeping, thermal fracture, dehydration stresses, [2] and sodium volatilization [15].

Mass-loss is not necessarily caused by just one of these mechanisms. Two, three, or perhaps even more mechanisms may be involved in an activation of an asteroid. [13] There has to be a source of particles as well as a mechanism to eject the particles from the asteroid [16].

The events of disruption are useful when studying the physical properties of asteroids. An impact can tell a lot about the properties, such as composition, of the surface material, and the strength and porosity of the asteroid. [13] Conversely, if something is known about the asteroid's composition or dynamical history, it can help determine suitable mechanisms of mass loss for the object and others like it [15].

Based on the size of the asteroid and the heliocentric distance of its orbit, one can roughly say which mechanisms are more likely than others. For example, sublimation can happen on asteroids of different sizes that are close enough to the Sun to be sufficiently heated, whereas rotational instability and electrostatic launch are more likely for smaller objects but can also happen farther from the Sun. Thermal processes and radiation pressure work better on small asteroids close to the Sun. Impact-induced disruptions, on the other hand, are possible drivers of activity for almost any object. [2]

Next, I will tell about each of the mass-loss mechanisms individually. Some of these mechanisms have been linked to real activity, while others are more theoretical. There is also a possibility that there are more drivers of activity that will be found by making more observations of real objects or models.

3.1 Ice Sublimation

Sublimation of ices is the best known of the mass-loss mechanisms, as it has been studied in the case of classical comets, whose mass is mainly lost by sublimation [2]. When the ice of a comet sublimates, the resulting gas drag forces can launch the released dust particles from the surface [16].

Sublimation can occur similarly on asteroids that contain ice. If the asteroid's ice surface has been exposed to the Sun and heated sufficiently, the particles may be ejected into space. [2]

The dust particles have to be small enough to leave the surface of the asteroid driven by drag from the sublimating gas. Grains of dust that are too big will remain and form a refractory mantle that will protect the ice surface and stop the sublimation. Ice can be preserved under a metre-thick layer of regolith for billions of years, and that is how some asteroids have managed to retain their ice content while orbiting closer to the Sun than classical comets. [2]

Sublimation is not the same on every body; it depends, for example, on surface porosity, nucleus rotation, heat conductivity of the material, and forming of a mantle. The asteroid belt is also not close enough to the Sun for all kinds of ice to sublimate. The ice has to have low albedo, which means that dirty ice will sublimate fast enough to drive activity on asteroids. [2]

For sublimation to happen on an asteroid, the contained ice has to be exposed to solar heating in some way. There may be a need for some other mechanism, e. g. impact, to first tear apart the mantle that has kept the ice safe from sublimation. [2]

3.2 Impact Ejection

Asteroid collisions are a relatively common phenomenon in the asteroid belt. Collision speeds are of several kilometres per second and thus collisions can be extremely erosive. [2] Asteroids do not have atmospheres shielding them from impacts—smaller impacts can form craters on the asteroid surface while larger impacts can entirely break the asteroid [4].

As a mass-loss mechanism, impact can cause two kinds of activity. The impact alone may shatter a part of the asteroid, or the impact may crater the surface and expose volatile materials for sublimation. Collisions are able to trigger activity on asteroids of almost any sizes, shapes, and locations in the solar system. [2]

If the collision itself causes the observable activity, mass is ejected from the collision site, and the particles that gain enough speed will escape the asteroid surface. Again the slower particles will stay to form a mantle. The escaping particles will form an ejecta plume around the asteroid, and this may cause a visible brightening of the asteroid, up to several magnitudes. [2]

Activity caused by collision will look different depending on the sizes and masses of the impactor and the impacted asteroid. The velocity of the impact will also affect the ejected particles. Models can be calculated of situations with different-sized bodies colliding. This means that the impactor size, for example, can be deduced by matching the observations to a model. [2]

The size of the impacted asteroid determines how the ejected material will be distributed in the appearing coma and how long the resulting brightening will last. Particles escaping from a larger asteroid will have to have bigger speeds, as the escape velocity depends on the size of the asteroid, and will travel away from the asteroid in a relatively short time. The ejecta from a smaller asteroid, on the other hand, do not necessarily need to be as fast and can take a longer time, and thus radiation pressure can have a more noticeable effect on the dust distribution. [2]

3.3 Rotational Instability

Rotating objects have a critical rotation period at which the centripetal acceleration equals the gravitational acceleration on the surface so that the object does not fall apart. Critical rotation period depends on the dimensions of the body and the density of its material. [2]

An asteroid may face rotational instability if its rotation period becomes shorter than the critical rotation period. At this point the asteroid rotates too quickly for its gravity and the tensile strength of its material to hold itself together, which can lead to rotational disruption. [2]

The distribution of asteroid rotation speeds shows that it is possible for rotational instability to drive mass-loss activity on some asteroids. There are small asteroids with enough tensile strength to withstand the fast rotation and avoid destruction. Larger bodies would structurally be weaker and more likely to be rotationally disrupted, but also less likely to rotate fast enough for disruption. Asteroids with rubble-pile-like structures are perhaps most likely to lose mass by rotational instability. [2]

Different kinds of torques can lead to the rotation of an asteroid to be destabilised. One possibility is collision between asteroids that can change the rotational speed. The Yarkovsky–O'Keefe–Radzievskii–Paddack or YORP effect caused by anisotropic photon radiation can accelerate the rotation on asteroids of smaller size. [2]

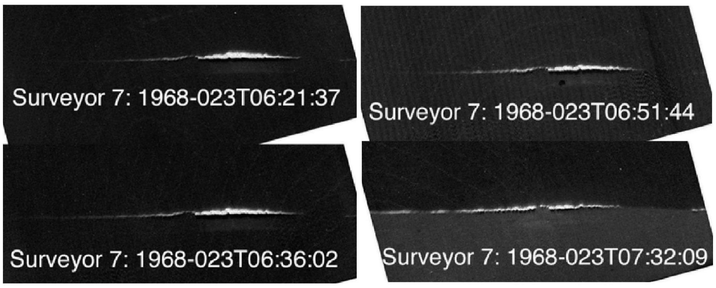

Figure 3.1: Photos of low-level Lunar Horizon Glow observed by Surveyor 7. White streaks are glows observed at different times. Image credit: NASA.

3.4 Electrostatic Repulsion

Electrostatic forces are capable of moving small dust particles on the surfaces of airless planetary bodies [17]. This kind of process was first known to happen on the Moon, where up to 10 μm dust particles can be seen floating above the surface, as shown in Figure 3.1. This phenomenon can be called 'horizon glow'. [2]

Electrostatic levitation on the Moon occurs because of a difference in potential on the dayside surface. UV and X-ray photons from the Sun cause a photoelectric effect and photoelectrons are ejected. This leads to a positive charging on the surface. [2] The region near the terminator becomes negatively charged due to a flux of solar wind electrons [17]. The potential difference results in an electric field with strong gradients near the terminator and shadow edges [2].

Now particles can be lofted and transported on the surface by electrostatic processes. On the Moon, which is closer to the Sun, the time of the charging is shorter than it would be on asteroids in the asteroid belt, but similar potentials could be achieved. [2]

In addition to the lofting dust on the surface of the Moon, electrostatic levitation may be the cause of other phenomena on different bodies in the solar system [18]. For example, the smooth dust ponds on the asteroid (433) Eros may have formed due to the sorting and depositing of finer particles of regolith in craters [19]. Similar ponds have potentially been found on the comet 67P/Churyumov-Gerasimenko [20].

The particles that are moved on the surface of the Moon will levitate, but mostly stay on the Moon because of its gravity. Asteroids, on the other hand, are much smaller bodies with weaker gravitational acceleration. The dust ejected by electrostatic repulsion could become fast enough to escape an asteroid's surface, which could lead to observable mass loss from the asteroid. [2]

3.5 Thermal Stresses

Asteroid can lose mass by thermal fracturing, which can happen due to excessive thermal stress on the material. Thermal stress is proportional to the thermal expansivity and Young's modulus of the body, and the temperature change that causes the stress. If the stress surpasses the tensile strength of the material, the material can fracture. [2]

Thermal fracture is capable of cracking fragments off an asteroid and also giving enough energy for small particles to escape asteroids of radius of up to a dozen kilometres. This requires temperature differences of 1000 K, which can only be reached if the asteroid's orbit passes the Sun at a close enough distance. [2]

Since most of the asteroids in the solar system are in the main belt on low-eccentricity orbits, they will not experience thermal fracturing. There are, however, some minor bodies for which this process is a possible mechanism of mass loss, because they get close enough to the Sun at perihelion to be heated sufficiently. [2]

3.6 Dehydration Stresses

Dehydration is a potential mass-loss mechanism for an asteroid that contains water in hydrated minerals. Carbonaceous chondrites, which are thought to be the typical materials of outer belt asteroids, may posess 10–20 % water in their hydrated minerals. The observable activity can be caused by the ejection of suddenly unbound water, or the body could crack because of the dehydration. [2]

The liberation of the water can occur in two different ways: either by thermal dehydration or shock dehydration. Thermal dehydration, much like thermal fracture, cannot happen for the majority of asteroids, because they are too far from the Sun. Laboratory experiments have shown that the activation energy for thermal dehydration requires a temperature of around 1000 K. [2]

Shock dehydration, however, could happen at any distance from the Sun. The shock waves of a collision can cause dehydration as the pressure can drive out the water bound to the minerals. The mass loss from dehydration could outlast the activity caused by the particles ejected by the impact itself. [2]

Shock dehydration as a mass loss process is probably not very prevalent, but it has to be taken into account since it might resemble a different situation. There is a chance of shock dehydration being misinterpreted as sublimation, since an impact can either lead to shock dehydration or exposure of material for sublimation, and in both of these cases the asteroid loses mass in the form of gaseous products. [2]

3.7 Sodium Volatilization

Usually any sublimation activity on comets and active asteroids has been found to be driven by the sublimation of water, carbon dioxide, or carbon monoxide ices. If all of the asteroid's surface minerals have been stripped of these ices, but mass loss still occurs, the next volatile substances to be sublimated should be something else. [15]

Recent studies and experiments on carbonaceous chondrite samples have found that sodium volatilization is a possible mass loss mechanism for asteroids that have already many times reached the temperatures where the ices sublimate and thus lost the ices. If sodium is present in an asteroid, in minerals such as sodalite and nepheline, it can be lost in a relatively short time of about 1 hour at temperatures of about 1000 K. Temperatures like this can be reached on asteroids that have low perihelia. [15]

3.8 Radiation Pressure Sweeping

Radiation pressure can sweep particles from an asteroid surface. Radiation pressure sweeping is not a mass-loss mechanism in the same sense as the other ones mentioned above, as it is typically merely able to remove particles from the asteroid surface after another mechanism has broken them off of the parent body. [2]

The asteroid cannot be larger than a dozen kilometres for the acceleration by radiation pressure to make the asteroid lose mass. Larger asteroids have stronger gravity which will prevent the small particles from reaching the required escape speed. [2]

Radiation pressure also affects the trails of particles of active asteroids that are already losing mass by some other mechanism, as it is the case for comets. If the particles are slow enough, the radiation pressure can shape the tail that is traveling away from the asteroid surface. [2]

4 Observations of Active Asteroids

4.1 Challenges of Asteroid Observation

Since the first find of an asteroid, 1 Ceres in 1801, more than a million minor planets have been observed. Half of them, almost 600 000, are numbered minor planets. [21] So, there are plenty of active-asteroid candidates, but the challenge is in finding out which ones of these are already active or can become active in the future.

The large quantity of asteroids can cause problems when deciding which ones to look at. Every single main-belt object can not be continuously monitored, and not all of them are going to activate during their lifetimes. On the other hand, short-term observations rarely catch any active asteroids, considering that their active period usually is on a short part of their orbit around the Sun. [3]

Potentially active objects in the main belt move on orbits similar to all the other inactive objects; they have low eccentricities, low inclinations and higher Tisserand parameters $T_J > 3$. Therefore they cannot be distinguished on dynamical grounds [3], unless they are main-belt comets from a family with a history of sublimation activity [22].

Most asteroids in the main belt are carbonaceous C-type asteroids. C-type objects are typically dark and have low albedo. [5] In addition to the dimness, asteroids are very small and therefore have low apparent magnitudes. The activity itself could also be too dim to be seen. Activity would easily pass unnoticed, if the asteroid was too far away or if it was hidden by the much brighter Sun. [13] The observation sensitivity and resolution has to be good enough to reveal whether the observed object has a coma or not [2].

4.2 Observing Active Asteroids

Active asteroids can be searched with surveys specifically dedicated to finding active asteroids, which include targeted and untargeted surveys [22]. Another means of finding them is inspecting data from more extensive surveys and archives [22, 23]. Either way, more surveys and better detection algorithms will help in the search [13].

Targeted main-belt-comet surveys are focused on objects that have promising physical or dynamical properties. Many main-belt comets can be discovered through this kind of surveys, but they consume time and narrow down the observed objects. Only using these surveys can lead to biased results, when all of the new active objects have similar qualities to the original ones. [22]

Almost every active asteroid has been linked to an asteroid family [24]. Objects in one asteroid family share dynamical and physical characteristics [3]. Disrupted asteroids have been associated with various different types of asteroids [24]. Many main-belt comets, on the other hand, have been linked to more primitive families that have more ice content [24], and if an asteroid in one family becomes active, it is perhaps worth looking at the other ones from the same family [3].

For example, when 133P/(7968) Elst-Pizarro activated due to sublimation, all the other Themis family asteroids became interesting from the active-asteroid-research point of view. The Themis asteroids supposedly have the same composition and could at some point become active as well if their volatile ices get exposed. [3] Later, two more main-belt comets have been found that are part of the Themis family [24].

Dynamical characteristics can help determine when to observe the chosen main-belt-comet candidates. Sublimation is caused by solar heating, which means that the activity will be most discernible near the perihelion of the orbit. [5]

Untargeted surveys require more asteroids to be surveyed to find active ones. Then again, selectional biases are lower in surveys with no special target, and they provide a better estimate of the population of active asteroids since any type of activity from any asteroid type can in principle be observed. Larger surveys with more than one objective can also be more efficient, because as much effort as in targeted searches is not needed. [22]

4.3 Examples of Known Active Asteroids

One of the obstacles in active asteroid research is the low number of examples that are known [13]. There are no more than two dozen known main belt comets or active asteroids [23]. Nevertheless, it is clear that the mass loss processes are surprisingly diverse [2].

Evidence has been found that mass-loss mechanisms including sublimation, impact, rotation, and thermal stress do in fact cause activity. There are still mechanisms, such as electrostatics, that have no confirmed real-life examples in causing asteroid activity. [2]

Let us go through three different examples of asteroids. Each of these can be assigned a suitable mass-loss mechanism. 133P/Elst-Pizarro is the representative of main belt comets, (596) Scheila is a clear example of impact ejection, and (3200) Phaethon is the only one that has been

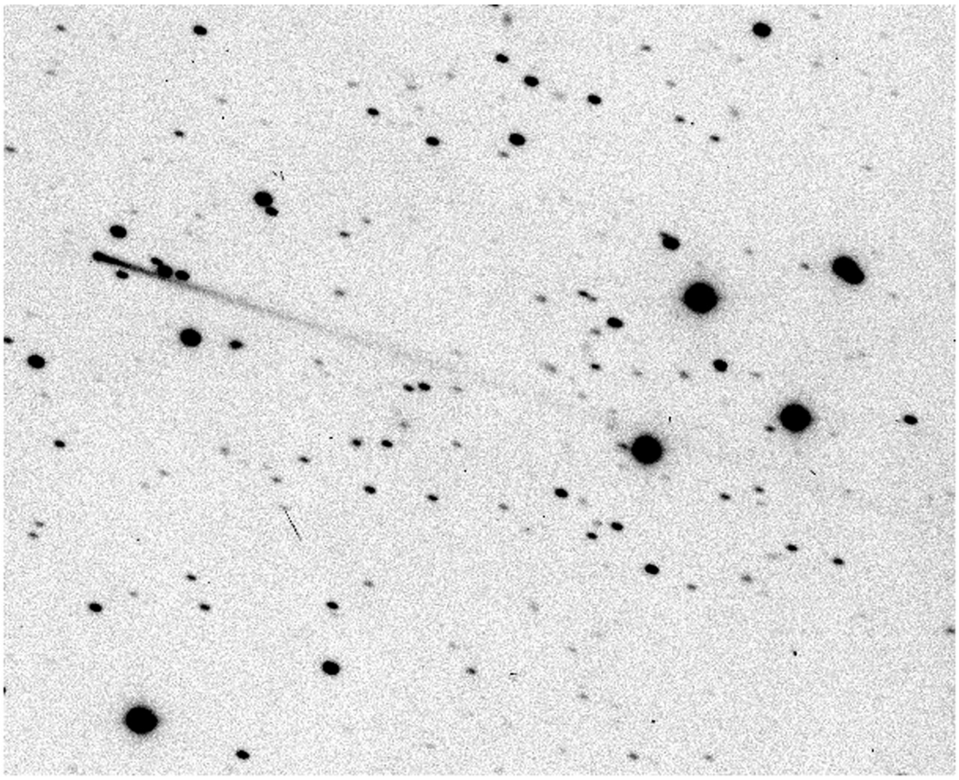

Figure 4.1: Main-belt comet 133P/Elst-Pizarro with its long, sublimation-driven dust trail, imaged in 1996. The nucleus is on the left with no coma, and the narrow tail extends across the image. Image credit: ESO. [25]

connected to thermal stresses [2] and vaporisation of sodium [15].

4.3.1 133P/(7968) Elst-Pizarro

133P/Elst-Pizarro was the first discovered active object in the main belt and, for a decade, it was the only known object of its kind. Initially, it was unclear whether Elst-Pizarro was a unique cometary object in the main belt or whether there were many others like it that had just not been observed yet. [3]

Discovered in 1979 and named 1979 OW_7, Elst-Pizarro was previously classified as an ordinary inactive asteroid. In 1996, however, it was observed to have a clearly visible dust trail. [3] Figure 4.1 shows Elst-Pizarro and its dust tail during an active period.

Elst-Pizarro is a smaller asteroid with a diameter of approximately 3.8 ± 0.6 kilometres. Its Tisserand parameter value is $T_J = 3.2$. [2] The fact that the asteroid Elst-Pizarro is on a stable main-belt orbit left the cause of the evident activation uncertain. The two options were impact and sublimation. [3]

Since impacts are not rare in the main asteroid belt, impact ejection would perhaps have been the simpler alternative of the mechanisms. In addition to that, no other cometary objects had been seen on similar orbits in the main belt. According to numerical models, however, a single impact could not have caused such a long-lasting phenomenon on this asteroid. [3]

The observed dust tail persisted for months, suggesting that the dust emission was due to sublimating ices. The trail did also not appear detached from the nucleus and it disappeared quickly, over weeks. [3]

Impact as the mass-loss mechanism was eliminated due to the asteroid's reactivation in 2002. Impact affecting the same asteroid in a similar manner six years later did not seem plausible. Emission modeling also suggested a longer lasting continuous emission model that is compatible with sublimation-driven activity. [3]

Asteroid (7968) Elst-Pizarro was given another name as comet 133P/ Elst-Pizarro. Elst-Pizarro can reactivate every 5.6 years when it gets close to the perihelion of its orbit. [5]

4.3.2 (596) Scheila

Asteroid (596) Scheila displayed a sudden increase of brightness in December 2010 [26]. Before its activation, Scheila had been known as an ordinary asteroid for a relatively long time, as it is a large main-belt asteroid that had first been observed in 1906 [27].

Images of Scheila were taken with different telescopes shortly after the activation was noted, and while the outburst of the asteroid was still visible. The mass-loss mechanism was deduced from these observations in different ways. [26, 28]

Figure 4.2 shows the diffuse coma that appeared around Scheila. The coma is asymmetric and spreads northward. It is shaped by solar radiation pressure, which slows and sweeps sunward-launched particles into the anti-solar direction. The mechanism involved in the smooth fading of the coma is also radiation pressure sweeping. [28]

Excluding some of the possible mass-loss-causing mechanisms is simple. First of all, Scheila's rotation period is 15.8 hours [27]. This means that its rotation is too slow to be the cause of instability [28].

Second, elecrostatic forces as the mass-loss driver can be ruled out due to Scheila's size. Scheila has an effective diameter of 113 ± 2 kilometres, and is therefore very large and has strong gravity. The escape speed the particles need to get out from the asteroid's surface cannot be achieved

Figure 4.2: Main-belt asteroid (596) Scheila exhibiting activity in 2010. The image shows Scheila and its expanding and fading coma in the middle. In the image north is up, west is right, and anti-solar direction is close to the westward direction. Image credit: Kevin Heider. [29]

by the electrostatic ejection. [2]

Thermal and dehydration related stresses can also be excluded by noticing that Scheila's low-eccentricity orbit is in the outer main asteroid belt, with a semimajor axis of 2.9 AU. The Tisserand parameter for Scheila is $T_J = 3.2$. [2] Scheila does not get close enough to the Sun to be thermally fractured.

The two remaining processes include sublimation and impact ejection. According to calculations, sublimation as the mechanism could be possible on two conditions. For observable activity to be caused at Scheila's distance from the Sun, there is a certain area of ice that needs to be exposed for sublimation. The dust particles must also be launched from the surface at speeds above the escape speed. Both of these terms would be achievable in theory. [28]

In reality, however, ice sublimation is not the mass-loss mechanism of Scheila. There are at least three problems with the sublimation hypothesis. The first one is the abrupt appearance and the fast fading of the coma. Sublimation would have caused a continued replenishment of particles and longer-term activity rather than an impulsive coma. [2, 28]

Another problem with sublimation arose in a spectroscopic observation study. None of the usual gases or volatiles that are present in cometary activity were detected in the material excavated from the asteroid Scheila during the active period. This means that a collisional disruption was the more plausible option. [26]

Finally, on Scheila, the volatile ices, if any, should have been preserved under a regolith layer. An impact would have been an obvious trigger of exposing the ice for sublimation, but the impact should have been big enough to uncover an area of ice large enough to drive the sublimation. The scale of the required impact would actually mean that the impact alone could cause the observed activity by ejecting dust. [28]

A match for the event was found through high-speed impact modeling. A decametre-sized object collided with Scheila obliquely from behind, causing the appearance of a triple dust tail consisting of an impact cone and a downrange plume of particles launched horizontally away from the impact site. Figure 4.2 shows both the northward and southward tail being swept westward, which is the anti-solar direction, by solar radiation pressure. [30]

In conclusion, Scheila is considered an unambiguous example of impact ejection. The activity was collision-induced and the resulting coma was shaped by radiation pressure. [13]

4.3.3 (3200) Phaethon

(3200) Phaethon is a near-Earth asteroid that has been linked to the Geminid meteor stream. Phaethon and the material of the stream have probably been part of a bigger parent body that has fallen apart tens of thousands of years ago, and nowadays, Phaethon is still disintegrating. Phaethon's decay has been observed as brightening at perihelion. [2]

Phaethon has a diameter of 6 kilometres and a Tisserand parameter of $T_J = 4.5$. Its highly eccentric orbit, with $e = 0.890$ [16], crosses the orbits of Mars, Earth, Venus, and Mercury, and gets closer to the Sun than any other numbered asteroid. [31]

Phaethon may have initially been on a lower-eccentricity Pallas-like orbit. If Phaethon's origins are near Pallas and other asteroids that are rich in volatiles, it is possible that it contains hydrated minerals that are dehydrated by the Sun. [2]

However, the temperatures on Phaethon have made it impossible for water to still be bound to the asteroids surface minerals. Moreover, based on spectral observations, Phaethon's surface seems to have no hydrated minerals, which makes thermal dehydration an unlikely mass-loss mechanism. [15]

As Phaethon's perihelion is so close to the Sun, the temperatures on Phaethon can reach 1000 K. Temperature of this order is enough for thermal fracture to happen. If the broken fragments were small enough to be picked up from the asteroid surface, they could be the mass that Phaethon has been losing. [2]

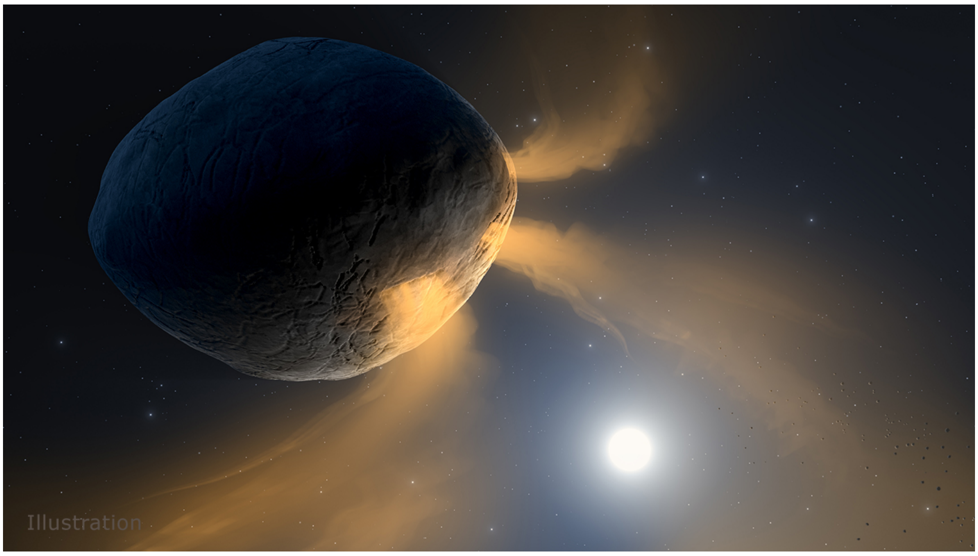

Figure 4.3: An artistic illustration of asteroid Phaethon with sodium vaporising in the heat of the Sun and venting into space. Image credit: NASA/JPL-Caltech/IPAC. [32]

There is another mechanism, also related to high temperatures, that could be responsible for the activity. For Phaethon's perihelion temperatures, water, carbon dioxide, and carbon monoxide ice have probably been lost a long time ago, but now it is possible for sodium to be sublimated. If the surface of Phaethon contains the right minerals, sodium could be vaporising and escaping. [15]

Sodium volatilisation is further supported by the fact that the sodium contents of the Geminid meteor stream are low. With sodium-venting Phaethon as their parent body, it seems plausible that the meteors have lost sodium before breaking apart. Sodium vaporisation could be the cause of the initial disintegration of the parent body and creation of the meteor stream, since in the past Phaethon could have contained even more volatile sodium. [15]

Phaethon's fast rotation may also be a factor in the mass loss. Phaethon has a rotation period of 3.6 hours, which, combined with its structural properties, can increase the mass that is shed. [33]

The visible activity is likely aided by solar radiation pressure that can swiftly sweep away loose particles. At perihelion, Phaethon is only

0.14 AU away from the Sun, and the effect of radiation pressure is significant. [2]

5 Future of Active Asteroid Research

It has now been established that there is, in fact, a continuum of active asteroids and main belt comets with a variety of mass-loss-inducing processes causing their activity. In the future, the obvious thing to do is to gather more information about these bodies and their mass-loss mechanisms.

One of the existing challenges to be worked on is the low number of known active asteroids. This problem is probably more about the need for more surveys and less about the actual occurrence of activity in the main belt, because, as explained earlier in the Section 4.1, there are many difficulties in the detection of these asteroids. [13]

New examples of real active asteroids can be found and confirmed by making observations of the activity with telescopes, while mass-loss processes can be studied by several different ways. Computer simulations, laboratory experiments and analyses, as well as spacecraft exploration can be helpful. [23]

Many kinds of numerical models and simulations for the rotational and impact disruptions of asteroids already exist. Laboratory experiments and statistical studies have been conducted to realize the possibilities of different disruptions. [13]

Available extraterrestrial rock samples can be used in laboratory experiments to see how the material reacts to certain conditions, which has been done, for example, in the case of sodium volatilization from asteroid-like material in high temperatures [15]. The conditions in which electrostatic forces cause dust lofting have also been studied in laboratory [17].

Discoveries and further observations of real active asteroids are needed so that the models and theories can be verified and adapted to represent actual situations [13]. One of the rarer and more expensive, albeit very useful, means of research is sending spacecraft into space for flybys, in-situ measurements, or even retrieving samples [23].

There are a couple of upcoming missions to active asteroids, including ZhengHe to main-belt comet 311P/PANSTARRS and DESTINY$^+$ to Phaethon, the active near-Earth asteroid. I will conclude this thesis by introducing both of them.

5.1 Upcoming missions

5.1.1 DESTINY$^+$ Mission on Near-Earth Active Asteroid (3200) Phaethon

Phaethon is a target of special interest as the active parent body of the Geminid meteor shower that recurrently hits the Earth with dust. DESTINY$^+$ (Demonstration and Experiment of Space Technology for INterplanetary voYage with Phaethon fLyby and dUst Science) is a JAXA (Japan Aerospace Exploration Agency) mission that will include a flyby of the active asteroid (3200) Phaethon. [34] The lauch is planned for the year 2024 [35].

Due to the high eccentricity and inclination of Phaethon's orbit, flyby is the only option for the mission. From the point of view of active asteroid research, the mission will focus on imaging and observing the asteroid on the close proximity flyby. The dust particles ejected from Phaethon will also be examined and the mass-loss mechanism either be confirmed or found out. [34]

The main instrument of the mission will be the DDA (DESTINY$^+$ Dust Analyzer), which is funded by the German Aerospace Center DLR and built by IRS (Institut für Raumfahrtsysteme) in Stuttgart, Germany. The DDA will operate during the entire flight of the spacecraft from Earth to Phaethon, collecting and analyzing dust. The instrument includes a dust detector and a mass spectrometer and it will be able to analyze the speed and direction of the incoming particles as well as their mass and composition. [36]

5.1.2 ZhengHe Mission on Near-Earth Asteroid (469219) Kamo'oalewa and Main-Belt Comet 311P/PANSTARRS

The first to target an object from the group of main-belt comets will be the CNSA (China National Space Administration) mission ZhengHe. It has two targets: near-Earth asteroid (469219) Kamo'oalewa and main-belt comet 311P/PANSTARRS. Its launch is planned for the year 2024, and it will be a decade-long mission. [37]

The ZhengHe spacecraft will make remote-sensing observations and retrieve samples from the surface of Kamo'oalewa, preparing to use methods of anchor-and-attach as well as touch-and-go. It will then bring a capsule of the regolith sample back to Earth, before heading towards the main-belt comet 311P/PANSTARRS. Both remote and in-situ measurements will be conducted at the MBC. [37]

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