

Asteroids, meteorites and Bering*

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Introduction

One of the largest remaining white spots in our Solar System is the asteroid belt. The asteroid belt bridges the gap between the terrestrial planets in the inner Solar System, and the large, primitive gas planets in the outer part of the Solar System. Of the 130.000 currently known asteroids, only one has been the main target of a space mission (the NEAR space probe to Eros), and only three others have been studied by passing space probes on their way to other targets.

Asteroids are highly interesting objects. They show a large variety in their physical properties, and they have a very fascinating dynamical history. Many of the remaining asteroids are too small, or formed too late, to produce sufficient heat to undergo a geological evolution. Therefore, they still contain primordial material dating back from the formation of the Solar System. Meteorites from these asteroids allow us to determine the age of the Solar System, and to study in detail the formation of the Solar System.

In the following, we will present a suggestion for a Danish space mission to explore the asteroid belt. In this manner, we will be able to contribute with a lot of new information, and be able to assist in diminishing this white spot. We have chosen to name the space probe Bering, after the Danish explorer Vitus Bering. Denmark is in a very strong position for this project, whose design is based on Danish developed technology. Due to the experience obtained from the first Danish satellite, Ørsted, and the large competence gained from Denmark's success as a space exploring nation, it will be possible to build Bering as a purely Danish project. Besides being scientifically and technologically innovative, the project is characterized by being relatively inexpensive, a rare thing within space exploration, and unprecedented for interplanetary missions of this kind.

The dynamics of asteroids

Since the first of January 1801, when the asteroid Ceres was discovered by Giuseppe Piazzi in Palermo, 130.000 asteroids have been found, of which more than 30.000 are in well determined orbits. Despite the large number of asteroids, the total mass is only around 2.3×10^{21} kg, or about 0.04% of the mass of the Earth.

Particularly the small masses of the asteroids compared to the masses of the planets, make the asteroids very dynamically active, i.e. large changes in their orbits can occur on relatively short time scales, typically between a few hundred to a few million years. A very important reason

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for this are the so called mean motion resonances between an asteroid, and for instance Jupiter, which is an integer relationship between the orbital periods of the planets. As an example, the 3/1 resonance means that every time Jupiter completes an orbit around the Sun, the asteroid has completed 3 orbits. These resonances strongly marks the dynamical distribution of asteroids in the asteroid belt, see figure 1.

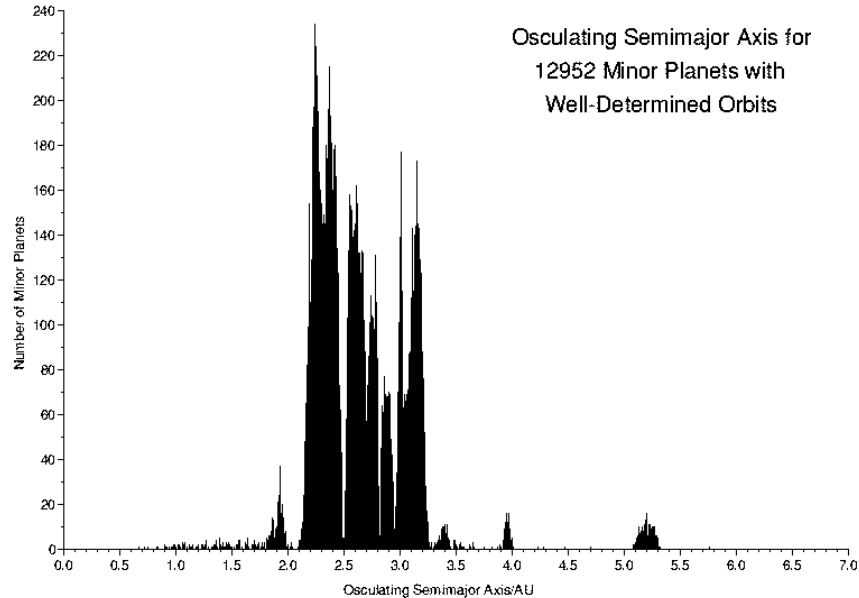


Figure 1: Overview of the dynamical distribution of the asteroids in the asteroid belt. The semi-major axes of the asteroids, relative to the Sun, is seen along the horizontal axis, while the number of asteroids is shown along the vertical axis. The figure is from Minor Planet Center, <http://cfa-www.harvard.edu/cfa/ps/mpc.html>

Immediately, it is possible to distinguish three large voids in the dynamical distribution of the asteroids, namely at the 3/1 resonance at 2.50 AU, the 5/2 resonance at 2.82 AU, and the 7/3 resonance at 2.96 AU. These gaps are together called the Kirkwood gaps. Other resonances lock the asteroids in certain orbits, as seen in figure 1: The group of asteroids called the Hilda asteroids in the 3/2 resonance at 3.97 AU, as well as the Trojan asteroids in the 1/1 resonance at 5.20 AU. The Trojans are actually two groups of asteroids, locked in the Lagrange points of Jupiter.

The reason for the formation of the Kirkwood gaps is that asteroids located in the mentioned resonances will have some highly chaotic orbits, and will go through drastic changes in their eccentricity, leading them to cross the orbit of Mars, and possibly the orbit of the Earth. The asteroids can then interact gravitationally with these planets, and even collide with them, and thereby disappear from the resonant regions.

Recent studies have shown that the dynamical properties of the asteroids in the asteroid belt is strongly dominated by a vast number of resonances with both the Earth, Mars, Jupiter, Saturn and Uranus, however without the same clear fingerprints as the resonances described above. These studies are important, as they can provide us with a purely dynamical evaluation of the number of collisions with Earth, but due to the very complicated dynamics, it takes many careful investigations to get this far.

Near-Earth Asteroids

A group of asteroids, that are currently studied intense, are the asteroids with orbits, that take them very close to the Earth with danger of collision, the so called Near-Earth Asteroids (NEAs). An asteroid is a NEA if the smallest distance from the Sun is less than 1.3 AU.

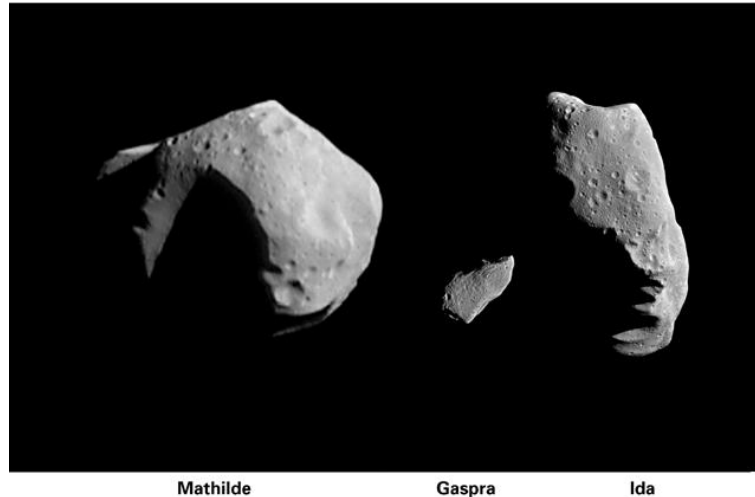


Figure 2: Three asteroids studied during flybys of space probes heading towards other targets. Mathilde is a so called C-type asteroid, imaged by the NEAR space probe on its way to Eros. Gaspra and Ida were the first two asteroids to be imaged in 1991 and 1993 by the Galileo spacecraft on its way to Jupiter. They are both S-type asteroids, like Eros. Ida was particularly interesting as it showed up to have a satellite, Dactyl. Mathilde is actually darker than Gaspra and Ida. The three asteroids are shown on the same scale. Gaspra measures about 12 km on the longest side.

That objects have collided with the Earth is witnessed by both craters on the surface of the Earth, as well as meteorites. The question is how often these collisions occurs today, and what the consequences are. Very intense search programmes have been initiated, in order to examine how many NEAs that actually exists. These search programmes have contributed with enormous discovery rates, currently between 2000 and 3000 new asteroids are discovered every month, of which around 30 are NEAs. It is however only relatively bright objects that are being discovered, which is mostly asteroids larger than 1 km. It is generally expected that many more smaller size NEAs exists, that may not directly threaten to extinguish all life on Earth, but which can cause severe damage.

Although we know that the Earth will be hit again, but we do not know how serious the current threat is, it is still too early to say whether there is actually reason to be worried by the danger for a collision. It can be thought, that the danger for a collision is small, compared to other dangers human beings are exposed to, but, on the other hand, the consequences of an impact could be very serious indeed, and our current knowledge of NEAs is still incomplete. In order to understand the dynamical mechanisms behind the NEAs, it is necessary to understand the dynamical mechanisms in the whole Solar System, and they are, as mentioned, marked by chaotic and resonant phenomena, with a high complexity. Hence it is difficult to give a precise estimate of the frequency of collisions with the Earth, as well as the consequences it may have for the Earth and the biological population. In this perspective, there is actually reason to take the problem with Near-Earth Asteroids serious, from that single motive to obtain an estimate of the actual danger.

Besides maybe being a threat for the Earth, NEAs are interesting objects to study, partly because their close approach to the Earth reveals interesting dynamical properties of minor planets in the Solar System, but none the least because fragments of the asteroids can be collected from the surface of the Earth as meteorites. As it is possible to make intense examinations in the laboratory of the geological composition of meteorites, where corresponding detailed examinations of NEAs still requires expensive space missions, it is by meteoritic studies possible to obtain information on the geological composition of objects in the Solar System, and to study further the formation of the Solar System. Therefore, there is a clear interest for a close collaboration between scientists studying meteorites, and scientists studying asteroids and the formation of planetary systems.

Type	Characteristica
C	Common in the outer part of the belt - probably related to CI and CM carbonaceous chondrites.
D	Dominates outside 3.25 AU. Redish, no meteorite analogs.
P	Common near the outer edge of the main belt. No meteorite analogs.
T	Rare and of unknown composition. Maybe transformed carbon chondrites.
K	Possible sources for CV and CO type carbonchondrites.
A	Rare type with redish spectrum. Contains olivine. Possible sources for brachinites.
M	Common in the main belt. Probably contains FeNi metal.
Q	Only three known asteroids. The spectra looks like the common chondrites.
R	Only one known, 349 Dembovska. Contain olivine, pyroxene and FeNi metal.
S	Very common in the inner part of the belt. Contain metal, olivine and pyroxene.
V	Vesta and a few related asteroids are the only known V-types. High pyroxene content.
E	Rare type, possibly related to enstatite chondrites.

Table 1: Overview of the different types of asteroids, ranked according to albedo. The first have an albedo less than 0.1, the latter more than 0.3.

Taxonomic classification

By determining the spectra of the reflected sunlight from asteroids, it is possible to determine the composition of minerals of their surfaces, and hence classify the asteroids. In this manner, the asteroids have been divided into 12 taxonomic classes, see table 1. As an example the asteroids Ceres and Mathilde are classified as C-types (see figure 2).

Box 1. Meteorites :

Meteorites consist of small fragments of about 130 different asteroids, the Moon and Mars. Those asteroids, from which we have fragments, are highly diverse, ranging from very primitive bodies, that have never been heated, to bodies that have been almost completely molten.

A meteorite originating from a body that has not been melted substantially (i.e. at most heated to 400 K during the formation of the Solar System), is called a primitive meteorite; the carbonaceous chondrites belongs to this group. They contain primitive material from the earliest phases of the Solar System - long before the existence of comets, asteroids and planets.

A meteorite is called evolved if it originates from an asteroid that has been heated substantially (> 1000 K). The choice of words is due to the fact that the high heating has partly melted the asteroid, and divided it into a core, mantle and a crust.

A developed asteroid that is broken into pieces will be able to provide many different kinds of highly different meteorites: (1) Iron meteorites, which are fragments of the iron-nickel core of an asteroid. (2) Stony-iron meteorites, from the boundary between the iron-nickel core and the silicate mantle. (3) Stony meteorites, or achondrites, originating from the crust.

The division between the classes are naturally not sharp, but rather smooth, and the mentioned 12 groups are therefore the main groups for the taxonomic classification. Besides the main groups, various sub-groups have been introduced, when none of the main groups seems to be fully appropriate.

The actual meaning of the main groups of the asteroids can be attempted to be determined by comparison with laboratory spectra of meteorites.

Meteorites

Except for a few meteorites from the Moon and Mars, most of the meteorites originate from the asteroids. Like the asteroids, the meteorites range from the very primitive carbonaceous chondrites to the highly evolved differentiated types, like iron meteorites (fragments of the iron core of an asteroid) and achondrites from the mantle and crust of differentiated asteroids. By looking at the chemical composition, the isotopic composition and mineralogy of the about 30.000 known meteorites, it is possible to divide them into about 130 different groups, where each group is assumed to originate from a single parent object. The number of meteorites in each group varies from approximately 10.000 in the largest group, down to just one.

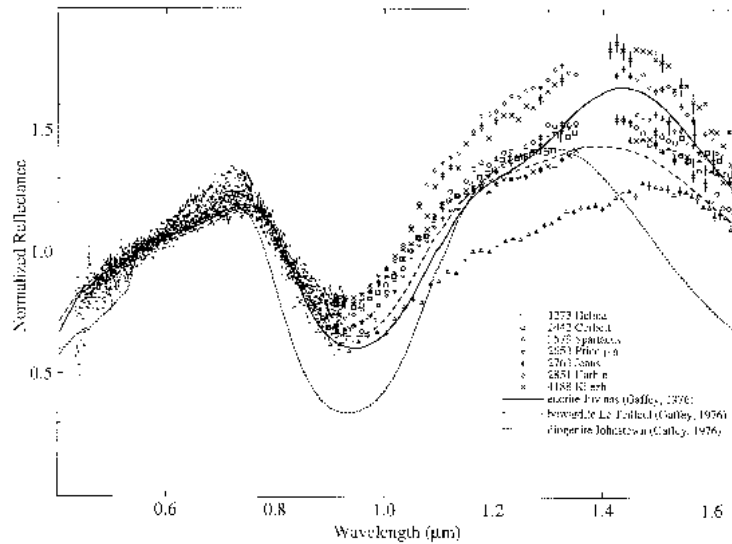


Figure 3: Spectra of the asteroids from the Vesta family (the symbols) compared to 3 different meteorite spectra (the curves). Shown along the horizontal axis is the wavelength, in this case the spectra extends from the visible to the near-infrared region. Along the vertical axis the normalized flux is shown (in asteroid language called reflectance). From Burbine et al. (2001), Vesta, Vestoids, and the howardite, euclite, diogenite group: Relationships and the origin of spectral differences. *Meteoritics and Planetary Science* 36, 761- 782.

By comparison of spectra of meteorites with spectra of asteroids, it is attempted to find those asteroids which are parent bodies for the individual groups of meteorites. This has proven to be very difficult. The only case where a relationship between meteorites and a parent body is between the HED meteorites and Vesta, see figure 3. In some cases, it can, of course, be due to the asteroid being completely crushed by a collision. When we for instance have fragments of the iron core of an asteroid, there is probably not much left of the original asteroid. Another important reason is believed to be due to the bombardment of the surfaces of the asteroids with particle radiation, that may change the spectral signature of an asteroid.

A very important task for an asteroid mission will therefore be to obtain a better understanding of the connection between meteorites and asteroids. The meteorites allow us to make detailed petrological studies, without knowledge of the regional geology. On the other hand, the asteroids allows us to study the regional geology without access to detailed studies.

Box 2. Differentiated planetary body :

The smaller planetary bodies in the Solar System (up to 10 km in diameter) have never been very warm. The heating of the smallest bodies in the Solar System is probably due to the decay of short-lived, radioactive isotopes, particularly Al^{26} . However, a small body radiates this heat almost as fast as it is created. Bodies, which quickly build up to more than 20-30 km in diameter, could due to a relatively small loss of heat, reach the melting temperatures of stone material^a. The reason for this is, that the production of heat is determined by the volume, that is, the amount of the radioactive isotopes, whereas the loss of heat is determined by the surface area. This means, that the large bodies have been self-heating! During the melting, iron and nickel sinks towards the core of the planet, while the silicates are deposited on top as a mantle, the cavities disappears, and the volume of the planet is strongly diminished. Another, and maybe more important factor is the time. Al^{26} has a very short half-life and can therefore have been burned out, before the last asteroids were formed in the outer part of the asteroid belt. This can be the explanation to, why the primitive asteroids apparently dominate in this part of space.

^aThe volume grows with the cube of the radius, whereas the surface area only grows with the square of the radius.

Bering, a possible first European Deep Space Mission

One of the largest challenges for the development of new scientific space probes is to ensure a still increasing yield of new, more advanced and more detailed measurements, simultaneously ensuring that the costs do not run wild.

This goal can only be achieved by continuously developing new principles of measurement for the instruments, as well as making the spacecrafts more and more independent, in order to reduce the operation costs. For instance, the Ørsted satellite operations only costs around 1% of the development and launch costs per year, compared to the NASA Voyager missions, that costed around 11% per year.

The fully automatic instruments of Bering actually makes it possible to make an almost fully automatic mission, with respect to daily maintenance. This is especially important when considering a deep space mission, with the long duration cruise from Earth to the target, the asteroid belt, as it would otherwise be very expensive to operate.

Due to the fully automatic instruments Bering will, as the first space probe ever, be able to detect, characterize and photograph small unknown asteroids in the Solar System. Earlier missions have been sent to already known asteroids, and have besides been switched off during the cruise phase. Therefore there is only a very poor knowledge of the density and the characterization of the smaller bodies in the asteroid belt. The results from the Bering mission will be able to provide us with a better understanding of the structure and development of the asteroid belt.

The star trackers

Bering is equipped with 6 star trackers which, while the spacecraft is slowly rotating around the symmetry axis ($1^\circ/\text{sec}$), scans the sky for asteroids: The computers of the star trackers continuously calculates the orientation of the spacecraft, based on the pictures of the sky made by the star trackers. The star trackers compares the images with stellar catalogs containing the 20.000 brightest stars. By the comparison, all luminous objects in the pictures which are not stars will be detected. Many of these objects will be galaxies, nebulae etc. but some will be asteroids. In contrast to galaxies etc. the asteroids will move relative to the background. And since the star trackers keeps a log of all luminous, non-stellar objects, the approaching asteroids will quickly be detected and followed. The star trackers, which are a further development of the star tracker

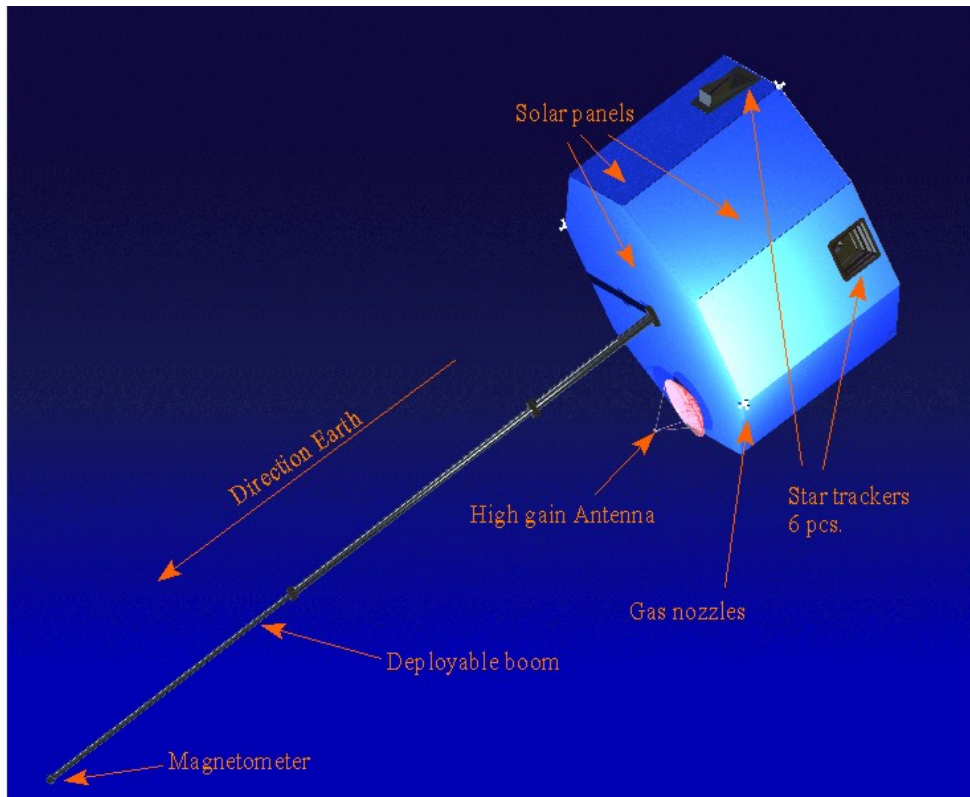


Figure 4: The characteristic shape of Bering, dictated by three factors: 1) The spacecraft must be slowly rotating in order to scan the whole sky; Rotational symmetry. 2) The sunlight is 6 times weaker in the asteroid belt than near Earth; hence there must be solar panels on all sides pointing towards the Sun. 3) The electric circuits will disturb the magnetic field close by; the magnetometer hence demands a long boom.

on the Ørsted satellite, are highly crucial for the mission. If they could not automatically detect an approaching asteroid, the image from the star trackers would first have to be sent to Earth, 400 million km away, corresponding to 20 minutes each way. Even if the ground station, ideally, could reply immediately, the asteroid would have been lost, before the commands for studying the asteroid would have been received. This fact is one of the main reasons, that we know so little about the asteroids.

The telescope

The heart of the group of instruments on Bering is a miniature multi-spectral imager, i.e. a telescope with a multi-color camera, which provides high-resolution color images of the asteroids. As seen on the sketch of the instrument, it is planned to have six bands, ranging from 2200 nm (infrared) to 350 nm (UV). The imager will take pictures of the asteroids passing close to Bering. The large folding mirror in front of the aperture of the telescope ensures that blurring due to the relative motion, does not destroy the images, when a fly-by of an asteroid is made with up till 5 km/sec. The mirror, which is relatively light, can easily be turned to track the motion of the asteroid, compared to moving the whole satellite.

The small, but powerfull, laser, seen in the middle of the telescope, is used together with an infrared detector in order to measure the distance to the asteroid. The laser will emit a short, powerfull pulse, simultaneously with starting a timer, the pulse will be reflected from the surface of the asteroid, and the timer will stop as soon as the detector registers the reflected pulse.

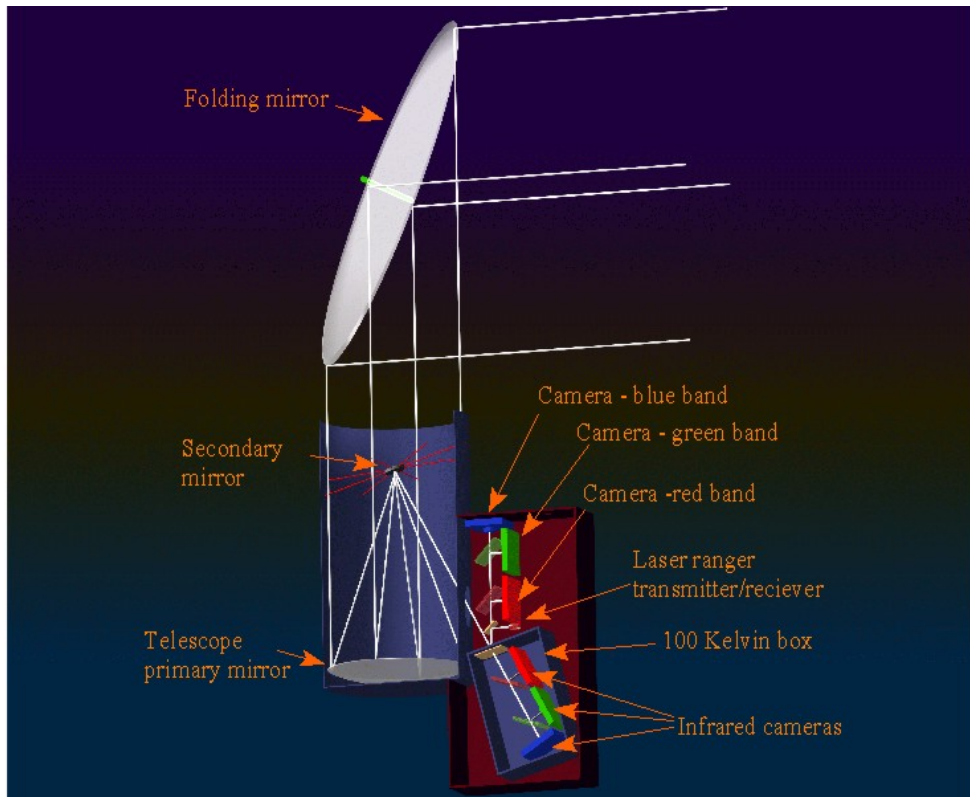


Figure 5: The fly-by of an asteroid will typically take place like this: The star trackers detects and track the asteroid at a far distance, while the asteroid still appears as a white dot, or a false star. When the asteroid approach, and an image can be obtained, the angle between the long axis of Bering and the direction to the asteroid will change. The closer the asteroid is, the fast this angle will change. In order to obtain good images, especially when the asteroid is at closest approach, the telescope is equipped with a so called folding mirror, which can rotate the field of view of the telescope, fast and precise.

The magnetometer boom

On the computer drawing of the spacecraft, the 6 m long magnetometer boom can be seen unfolded. The purpose for placing the magnetometer on the long boom is to measure a magnetic profile of the asteroids of close approach. The magnetometer is placed on the long boom, in order to avoid the disturbances from the satellite itself. In Deep Space, the magnetic field is very weak, typically 1-10 nT, but particularly asteroids with iron cores will be detectable from a considerable distance. The magnetic signature of the asteroids is one of the most important classification parameters, next to the spectral measurements. The NASA space probe "NEAR" did carry a very sensitive magnetometer, but was unfortunately unable to provide usable results, due to disturbances from the satellite itself.

The spacecraft

The 8 side panels and the bottom are covered by solar panels providing the electric energy for the batteries and the electric equipment on board. However, the top of the satellite is covered with a special surface covering, a so called Second Surface Mirror (SSM), which works as a cooling surface for the infrared cameras in the multi-spectral imager. As the wavelengths to be measured by the imager are close to and in the wavelength band of radiative heat, it is necessary to cool the detectors in the cameras to 80-100 K to ensure a reasonable signal-to-noise ratio. A SSM is typically made by a panel layered with a film of Kapton tape. The Kapton tape is prepared with a 5 μm aluminium mirror, again covered by a 20 μm quartz layer. The radiation from the Sun can

pass the quartz layer, and is reflected from the aluminium layer, exactly as a normal mirror. Hence it is ensured that only very little heat is absorbed, whether the radiation from the Sun is falling on the surface or not. The quartz layer is not transparent for radiative heat. However, as quartz is a fair heat conductor, the heat from the panel is led through the thin Kapton, aluminium and quartz layer to the surface, where it is radiated to space. One of the "coolest" surface coverings can be obtained in this manner.

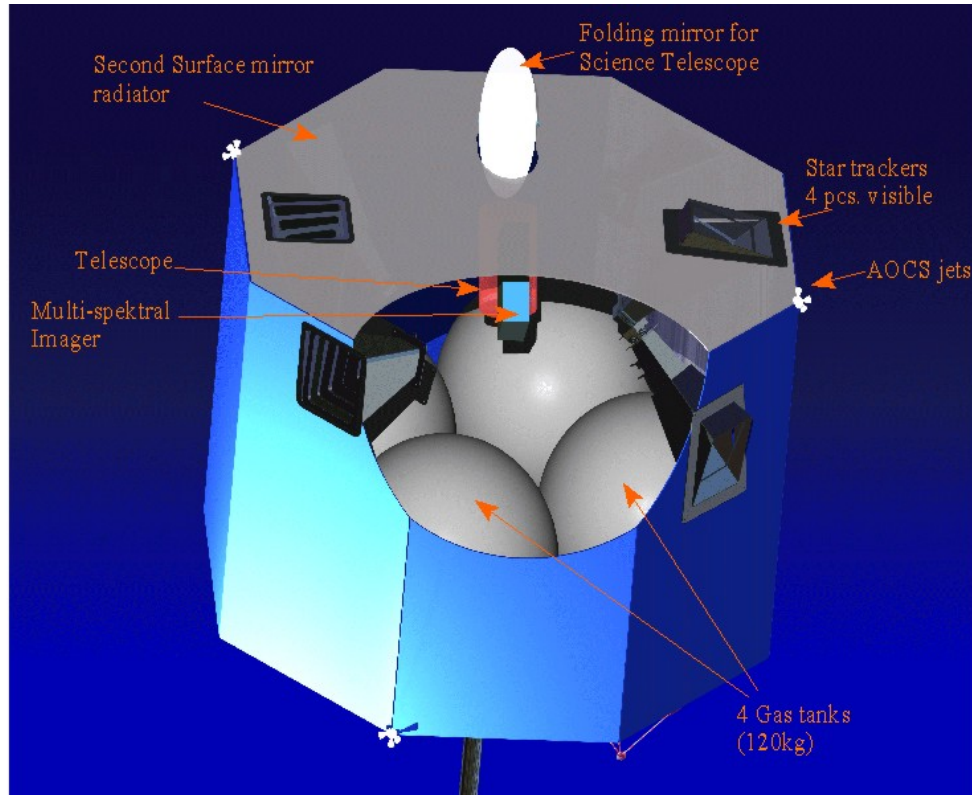


Figure 6: The scientists would like to get as close as possible to pre-chosen objects, as well as to be able to approach new discoveries, in order to obtain good images. Such manoeuvres requires a powerfull manoeuvre system of cold gas, which, as can be seen in the image, occupies the largest part of the interior of the spacecraft.

The power supply and contact with Earth

Bering is a relatively large satellite, 1.2m on each side, with the boom folded in launch configuration. This size is not as much dictated by the instruments and other equipment, as it is due to the demand for sufficient electric power. At Earth, the solar panels of Bering can supply more than 300 W of electric energy; at the asteroid belt the solar radiation is 5-6 times weaker, so here there is only 45 W available where the distance to the Earth is the largest, and where most energy is needed for the radio link.

Besides working as attitude instruments and asteroid detectors, the star trackers also provide another highly important measurement. By detecting and tracking known celestial objects, the star trackers can calculate a rather accurate position of the spacecraft. This position, and the easily calculated current position of Earth, can be used to find the direction from Bering to Earth, and hence the small, but very direction sensitive antenna, can be pointed directly towards Earth. Also this funtion is fully automatic.

Box 3. Center for Planetary Research :



February 2001, a group of scientists from the Niels Bohr Institute for Astronomy, Physics and Geophysics (NBIfAFG) moved together with a group of scientists from Danish Space Research Institute (DSRI) to the Center for Planetary Research. The center is physically located in a building next to the Rockefeller-complex in Copenhagen, where the astronomers, geophysicists and DSRI are resident. The idea with the center is to enhance the research in topics related to the Solar System, as well as to provide improved possibilities for students at NBIfAFG to specialize within this field. The group behind the center is highly interdisciplinary, with competence in the disciplines: Astronomy, geophysics, physics, space instrumentation, geology and biology. The Bering mission described here is an example of the outcome that can be obtained when bringing people with different scientific background and common interests together. Read more about the Center for Planetary Research at <http://www.planetcenter.dk>.

This last functionality is actually what ensures the largest cost reduction of the mission, as well as provides a large assurance for success: Normally a spacecraft like Bering would require a very large antenna with a very powerful emitter, and a very sensitive transmitter, in order to find the Earth again, if orientation is lost. It would also be necessary to send a homing signal from Earth, at regular small intervals, in order to avoid the antenna pointing off the direction to Earth. Furthermore, if the asteroid is hit by some gravel in space, as must be expected to occur in the asteroid belt, such an event can be fatal, if it is not possible to re-establish radio communication. With the navigation module of Bering, as well as some intelligent software to control the instruments on board, Bering will be able to take care of itself most of the time, as neither constant survey, tracking or powerful antennas are required from Earth. Bering will just have to be commanded to start transmission of data at a time suitable for the ground station. This is highly different from previous deep space missions, and neither NASA nor ESA does yet master this technology.