7

The Long Trek

7.1 EARLY COMMISSIONING

Although Rosetta was rapidly leaving Earth behind after launch at 07:17:44 UT on 2 March 2004, there were many checks to be carried out before the mission team could celebrate this achievement.

First, the venting and priming of the propulsion system was completed at 09:44 UT. The reduction of the spacecraft's initial spin rate and the Sun acquisition phase also proceeded very smoothly. Once the deployment of the huge solar arrays was completed at 10:11 UT, power started to flow. Next was switching on and testing the two star trackers required for stellar navigation and attitude control. The launch locks of the Philae lander were released successfully at the end of the first ground station pass. It would remain firmly attached to the spacecraft by the cruise latches until its release at the comet.

Another major milestone was passed at 00:34 UT on 3 March when the high-gain antenna was deployed, starting with firing the pyros of the launch locks. This was followed by three rotations, first in elevation, then in azimuth, and finally an azimuth-elevation slew that ended with the 2.2 meter dish aimed at Earth.

Later that morning, Rosetta completed its first trajectory correction maneuver – a test that changed its velocity by 1 m/s. After the spacecraft had adopted the requisite orientation, the 7 minute burn was initiated at 11:49 UT. The thrusters and the attitude and orbit control system (AOCS) performed flawlessly.

The mission operations specialists at ESOC completed their calculations and confirmed that the launch vehicle had put Rosetta on a highly accurate trajectory. Owing to the spacecraft's excellent performance and the progress of planned activities, it was decided to bring forward commissioning activities for the platform and payload.

P. Bond, *Rosetta: The Remarkable Story of Europe's Comet Explorer*, Springer Praxis Books, https://doi.org/10.1007/978-3-030-60720-3_7

Activation of S-band transmission using the high-gain antenna got underway at 23:16 UT on 3 March. Successful commissioning of the S-band uplinks and downlinks using the low-gain and high-gain antennas proceeded throughout the night. Configuration of the high throughput X-band link using the high-gain antenna was accomplished by a downlink signal received by both the ground stations at Kourou and Madrid at 13:07 UT on 4 March. After the S-band uplink was terminated at 13:20 UT, the X-band uplink was established at 13:35 UT. When this was terminated at 14:30 UT, uplink communication was re-established using S-band and the high-gain antenna.

These tests successfully demonstrated the nominal performance of the major communication systems, which would be critical for the mission's success. However, the results had shown that a maximum data rate of 22 kbits per second was sustainable using the high-gain antenna.

Meanwhile, owing to the rapidly increasing distance from Earth, the possible telemetry data rate using the low-gain antenna had already decreased to 7.8 bits per second and the antenna would soon become redundant until the next Earth fly-by.

During this time the attitude control system was subjected to various tests, such as gyroscope calibrations and determination of the friction in the reaction wheel system. This included, for the first time, switching on all four reaction wheels simultaneously. Substantial disturbance of the spacecraft's orientation caused by outgassing occurred during the first few days, but these torques gradually decreased to nominal levels.

Full configuration of the 25 Gbit solid-state mass memory took place on 4 March in order to support routine operations, creating data stores for all instruments and storing redundant files of application software. Activation of all memory modules for the mission was successfully completed.

Commissioning of the power subsystem took place at the end of the Madrid pass on 4 March. All checks were successful and the power subsystem behaved as expected.

The drive mechanisms of the solar arrays were employed during the early days of the flight in order to keep the solar cells perpendicular to the Sun as the spacecraft rotated – thus providing maximum power.

The Launch and Early Orbit Phase (LEOP) was completed successfully on 5 March, clearing the way for the Mission Control Team at ESOC to move from the Main Control Room to the Rosetta Dedicated Control Room, in readiness for commencement of the initial phase of the commissioning program. From now on, primary communications links were provided solely by the ESA ground station at New Norcia, Australia, which could provide coverage for 10-12 hours per day.

7.2 INITIAL PAYLOAD TESTING

As Rosetta headed into deep space and closer to the Sun, it maintained the ‘tilted’ orientation achieved during LEOP and was slewed to +X Sun-pointing only when this was required for payload operations. This kept the high-gain antenna mechanism cooler, after an unexpectedly high temperature was measured in LEOP. This had no immediate impact on operations, apart from imposing additional attitude slews, which in turn meant more reaction wheel off-loading cycles.

Attention then turned to the commissioning of Rosetta’s scientific payload, scheduled to take place throughout March, April and May. The instruments were activated one at a time, with experts from the instrument teams present at ESOC during the daily ground contacts with the spacecraft.

The first three instruments to be activated were COSIMA, CONSERT and OSIRIS, and their first commissioning activities were successful. On 10 March, the CONSERT antenna was the first payload appendage to be deployed.

For five days in mid-March, mission controllers concentrated on commissioning the Philae lander.

Rosetta instrument commissioning resumed with the RPC on 18-19 March. On the second day, spacecraft booms carrying the RPC MIP (Mutual Impedance Probe) and LAP (Langmuir Probe) instruments were successfully deployed using the primary systems. As the instruments were active for the deployment, the science telemetry confirmed the success of the operation. However, in order to analyze a failure that was identified in the redundant power supply, the remaining RPC activities were postponed to a later date.

The following week saw ROSINA, ALICE and VIRTIS activated for the first time, with successful completion of their initial commissioning activities.

At the end of March, the RSI was commissioned during four ground passes, followed by the initial activation and commissioning of the MIRO instrument. This coincided with several software maintenance activities on the spacecraft. In early April, MIRO commissioning was followed by the commissioning of GIADA and MIDAS. With all of the scientific instruments having been successfully activated at least once since the start of the mission, this marked an important milestone.

Meanwhile, a new attitude pointing mode (known as GSEP Earth-pointing) was initiated and maintained for most of the year. Periodic re-pointings to prevent the Sun coming too close to the +X spacecraft axis were planned, typically once per month.

When priority use of the New Norcia ground station was temporarily assigned to support the main science phase of ESA’s Mars Express mission, Rosetta’s daily sessions were reduced to about 7 hours.

7.3 ASTEROID SELECTION

Rosetta's scientific goals always included the possibility of studying one or more asteroids at close range, but only after Rosetta's accurate insertion into an interplanetary orbit could the ESA mission managers assess how much fuel was actually available for fly-bys. Information from ESOC enabled the Rosetta Science Working Team (SWT) to select a pair of asteroids of high scientific interest in orbits between those of Mars and Jupiter that were reachable within the fuel budget.

On 11 March, the SWT made its final selection of (2867) Steins and (21) Lutetia. These were contrasting objects, both in terms of size and physical properties.

Steins was known to be relatively small, with a diameter of a few kilometers. The fly-by was set for 5 September 2008, during Rosetta's first excursion into the asteroid belt, at a range of just over 1,700 km. The encounter would be at the relatively low speed of about 9 km/s.

Ground-based studies had shown Lutetia to be a much bigger object with a diameter of about 100 km, but little was known of its composition. Rosetta would pass within 3,000 km of it at a speed of 15 km/s on 10 July 2010, during its second venture into the asteroid belt.

In addition to close-up images of these primordial objects, Rosetta would supply data on their mass and density as clues to their composition, measure their temperature, and search for any nearby gas and dust.

7.4 COMMISSIONING, PHASE 2

The second phase of lander and instrument commissioning was carried out during April. One minor glitch was the failure of the prime explosive pyro to fire on the first attempt to open the door on the ALICE detector. After an investigation, the redundant pyro was fired successfully and the door safely opened.

On 23-25 April, the spacecraft was rotated to point its payload toward Earth for the first time. This gave MIRO and VIRTIS the opportunity to take calibration measurements, with Earth as their target.

There was some concern about the effects of increasing temperature as Rosetta continued to cruise nearer to the Sun. An unplanned slew was executed to change the spacecraft's attitude when the –Z thrusters reached the highest permitted temperature. Monitoring of the thermal environment resulted in a further restriction on the range of allowed spacecraft attitudes. The Sun would be restricted to –4 and +50 degrees from the +X axis within the X/Z plane, at least until after perihelion on 25 May.

The second slot of commissioning OSIRIS was achieved on 25-30 April, with the exception of the planned Earth-Moon imaging, which was postponed as a result of the limits imposed in response to the high thruster temperatures that occurred during the Earth-pointing period for the MIRO instrument.

Rosetta's first scientific observations took place on 30 April, when MIRO, ALICE, VIRTIS and OSIRIS took spectra and images of Comet C/2002 T7 (LINEAR), which was making its first (and only) visit to the inner Solar System. The coma and tail were studied at wavelengths ranging from the ultraviolet to microwave portions of the spectrum, from a distance of about 95 million km. The presence of water molecules around the comet was identified. Follow-up observations by ALICE and MIRO were made on 17 May.

Fig. 7.1: An image of Comet C/2002 T7 (LINEAR) taken in blue light by the OSIRIS camera on Rosetta. It shows the comet's nucleus from a distance of about 95 million km, with the tail extending over 2 million km. (ESA/MPGH/H. Uwe Keller)

Even though the calibrations of the instruments remained to be completed, the data from the remote sensing observations confirmed their excellent performance.

As the insolation increased, the thruster modules on the +X side of the spacecraft continued to warm up, and by 7 May the hottest module, number 7, had reached 65°C.

Preparations for the first deep space maneuver – a long burn of the thrusters – commenced on 6-7 May by firing a dozen pyro valves to enable pressure regulators to link the high-pressure helium tanks to the propellant tanks.

Rosetta's first major propulsion burn was completed successfully on 10 May. This was the most critical spacecraft activity executed since LEOP, the maneuver produced a change in velocity (delta-V) of 152.8 m/s. This was achieved through a continuous burn of the four axial thrusters over a period of about 3.5 hours. The performance of the spacecraft was excellent, within about 0.05% of nominal.

A 'touch-up' maneuver was made on 16 May, as part of the trajectory targeting activities around perihelion. This burn of less than 17 minutes gave a delta-V of 4.989 m/s. Having achieved the desired trajectory, the reaction control subsystem was isolated on 24 May.

Rosetta reached perihelion at 17:00 UT on 24 May. Its minimum distance from the Sun was 132.6 million km (0.886 AU). At the end of the last New Norcia pass on 28 May, Rosetta was 40.3 million km from Earth and the one-way signal travel time was 2 minutes 14 seconds.

With Rosetta now beginning to move away from the Sun and follow a circuitous path back to the vicinity of Earth, the main commissioning activities got under way.

The Cruise 1 Phase formally began on 7 June 2004, and was expected to last until the start of the second (and final) commissioning slot in September-October 2004. It required the parallel activation of all onboard instruments, and special pointing activities designed to calibrate the remote sensing payload. At the same time, the period of non-contact with the spacecraft was gradually increased, culminating in weekly passes by mid-July.

During June, the attitude and orbit control system was checked and updated, and the medium-gain antenna was brought online as a precaution, in case the loss of the high-gain link should prompt the spacecraft to adopt 'survival mode'.

Starting in the fourth week of the Cruise 1 Phase, Rosetta was configured for 'quiet cruising' for the first time and the payload remained off, with no test, maintenance or characterization activities taking place.

The uplink and activation of new onboard avionics software (version 7) was undertaken over 16-23 July. The mission team judged this "probably the most critical operation since launch". This successfully concluded four months of intense system testing at ESOC.

The activation of the new software involved commanding a reboot of the Data Management and Attitude and Orbit Control Systems on 22 July. This automatically put the spacecraft into safe mode. It was the first time that safe mode had been entered in flight, but the automatic reconfiguration operations and six hours of manual recovery controlled from ground went as planned. Once verification of the new software was completed on 2 August, it took over full control of the spacecraft.

Following verification of the low-gain and high-gain antennas, the second part of the main commissioning phase began on 6 September. This incorporated payload software updates and full functional testing of each instrument. The commissioning was completed in mid-October, after which the baseline attitude of the spacecraft was changed to +X Earth pointing until it was time to prepare for the first Earth flyby.

Rosetta entered cruise mode again on 17 October. Apart from routine flight operations and monitoring tasks, the mission team used this time to perform some troubleshooting activities. These included a health check of the star trackers and activation of the OSIRIS instrument on 20 January 2005. OSIRIS received a software upload designed to solve an issue with its door mechanism that was discovered during the commissioning phase, but follow-up tests showed the update had not solved the problem. Nevertheless, the instrument was able to take pictures of Comet Macholtz as part of the verification of its operations.

7.5 EARTH FLY-BY #1

Fly-bys make use of the gravitational attraction of planets to modify a spacecraft's trajectory and achieve the orbital energy needed to reach the final target.

Rosetta's first Earth swing-by would be an essential gravity boost in its 10-year, 7.1 billion km trek to Comet 67P/Churyumov-Gerasimenko. Several small tweaks to its trajectory were made in preparation for the Earth fly-by. These culminated in TCM-6, on 17 February 2005, which was so precise that a back-up maneuver planned for 24 February was cancelled.

The spacecraft was gradually configured for the gravity assist, including activating its fourth reaction wheel on 25 February, switching its radio communications from X-band to S-band on 27 February, and shifting from the high-gain antenna to the low-gain antenna on 2 March.

Rosetta was given ground coverage priority from 27 February to 10 March, with daily New Norcia passes that supported the various maneuvers and provided the tracking data needed to accurately calculate the fly-by geometry.

On 1 March, the first payload instruments were activated: RPC and ROMAP on the lander. These were followed by MIRO and VIRTIS on 4 March. Meanwhile, SREM, the radiation environment monitor, was active in the background. Another lander instrument, ÇIVA, was operated for three hours around closest approach. The OSIRIS imager was not able to operate due to unresolved problems with its instrument cover.

Fig. 7.2: Earth viewed by Rosetta's navigation camera from a distance of about 250,000 km after the fly-by on 4 March 2005, featuring South America and Antarctica. (ESA)

The first Earth fly-by took place at 22:09 UT on 4 March 2005. The spacecraft approached from the night side, and the closest point of approach was above the daylight hemisphere. During the passage, the spacecraft seemed to fly to the west and disappeared from view on the day side. ESA's closest-ever Earth fly-by up to that time saw the spacecraft pass above the Pacific Ocean, just west of Mexico, at an altitude of 1,954.74 km and a relative velocity of 38,000 km/h.

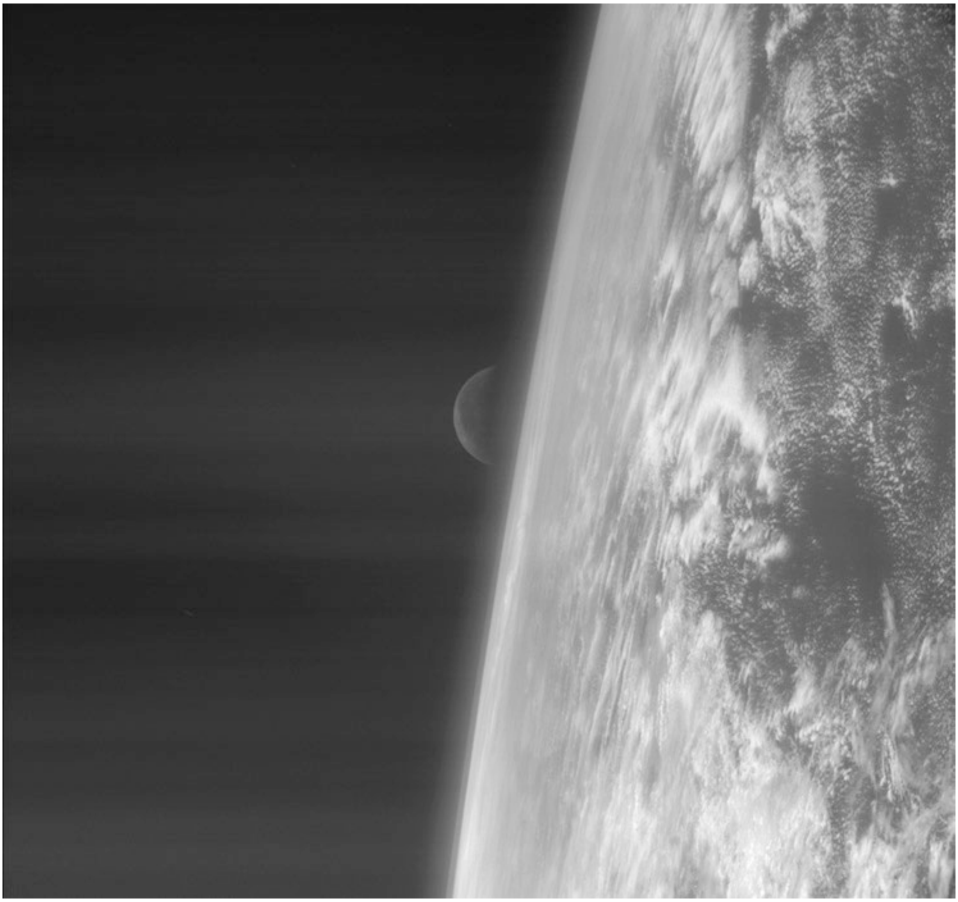

Fig. 7.3: An image of the Moon rising over the Pacific Ocean at 22:06 UT on 4 March 2005, taken by a navigation camera just three minutes prior to the point of closest approach. (ESA)

The Earth swing-by included various tracking tests with the navigation cameras, using the Moon as a target, as Rosetta approached on 4 March. All operations were successfully completed – with the exception of a problem in configuring the link between Camera B and the spacecraft's mass memory that prevented the pictures from this camera being stored.

The spacecraft was commanded at 01:00 UT on 5 March into Asteroid Fly-by Mode, using the navigation camera aimed at the Moon to control its attitude. In this special mode, Rosetta made use of the NAVCAM to steer in such a way that the payload platform was kept pointed towards the target. This was the first and only in-flight test opportunity for this mode, which was solely intended to be used operationally during the actual fly-bys of the asteroids Steins in 2008 and Lutetia in 2010. The test lasted 9 hours and was fully successful. After the end of the test, the spacecraft was pointed back Earthward to enable the payload instruments and the navigation cameras to take black-and-white Earth pictures and other measurements from a rapidly growing distance of about 250,000 km.

Fig. 7.4: Rosetta's VIRTIS instrument took this composite infrared view of the Moon on 4 March 2005, prior to closest approach to Earth, from a distance of 400,000 km. The spatial resolution is 100 km per pixel. It combines images at three different infrared wavelengths (2,225, 3,000 and 3,650 nanometers). Red represents the basaltic plains known as 'maria', while blue represents the ancient highlands. (ESA)

On 4-5 March, prior to closest approach to Earth, VIRTIS took a series of images in visible and infrared light at a distance of 400,000 km from the Moon. From its perspective, the Moon was a crescent with only a small portion of the surface illuminated (ranging between 19% and 32%). The infrared images detected both thermal (heat) radiation from the lunar surface and reflected solar radiation. The spatial resolution was low but it was still possible to distinguish Oceanus Procellarum, Kepler crater and Mare Humorum (see Fig. 7.4 and Fig. 7.5). Spectral analysis distinguished the mineralogical differences between the flat 'seas' (in Latin 'maria') and the highlands. For instance, it was possible to see marked differences in the abundance of two kinds of rocks known as pyroxene and olivine.

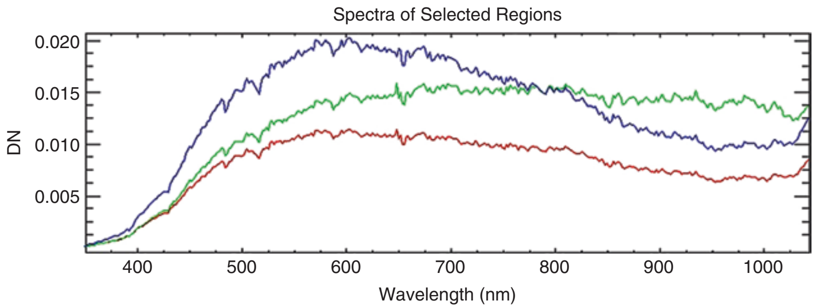

Fig. 7.5: VIRTIS infrared spectra of Kepler crater (blue), Mare Humorum (green), and Oceanus Procellarum (red) on the Moon. The spectra are uncorrected for the phase angle. Despite the low spatial resolution of this instrument's images, the mineralogical differences between the highlands and the basaltic plains ('seas' or 'maria') were evident. (ESA)

On 5 March, after the closest approach to Earth, VIRTIS took a series of images of our planet in visible and infrared light from a distance of 250,000 km. Only 49% of it was illuminated, but the instrument was able to detect infrared radiation emitted from both the day and night hemispheres.

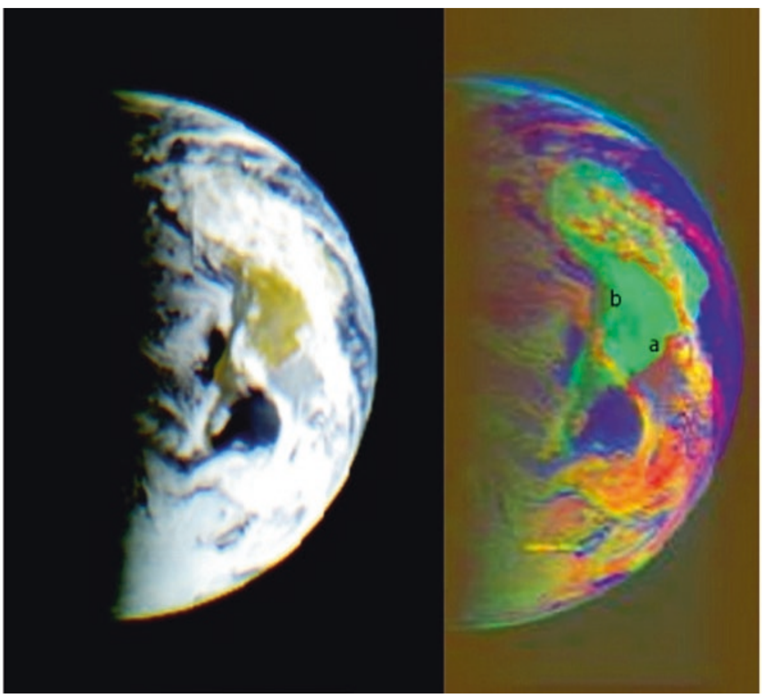

Fig. 7.6: A composite red-green-blue image (left) and stretched false-color image (right) of Earth in visible light from the VIRTIS instrument. It is possible to distinguish Argentina (a) and the Andes mountain chain (b). (ESA)

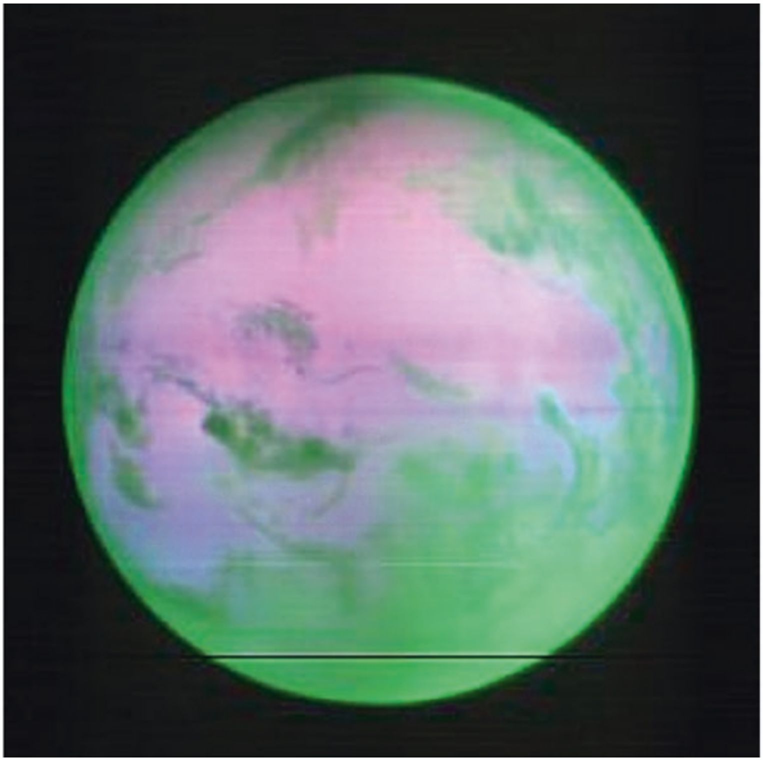

Fig. 7.7: An infrared image of Earth from the VIRTIS instrument taken from a distance of 250,000 km on 5 March 2005, after Rosetta's closest approach. It shows the distribution of carbon dioxide in the atmosphere, with higher concentrations in the green areas. The spatial resolution is 62 km per pixel. (ESA)

VIRTIS was switched off on 5 March, followed by MIRO. Next was the lander's ROMAP and RPC on 7 March. ALICE was activated for various slots on 8-9 March. The radio link was configured back to S-band using the high-gain antenna on 6 March, and a new Earth-pointing attitude was initiated on 8 March. Downlinking the science data from the fly-by was completed on 10 March.

At the Science Working Team's meeting at ESOC on 8-9 March, the principal investigators presented the preliminary results from their instruments during the fly-by, and expressed their satisfaction.

The final observation during the fly-by phase was on 26 March, when ALICE made another observation of the Moon.

7.6 ACTIVE CRUISE AND DEEP IMPACT

A passive checkout of the payload in late March found an anomalously high electrical current in MIDAS, so the instrument was shut down for several weeks until functional tests could be arranged.

During much of April and the first half of May, the mission team carried out the first in-flight test of the Near Sun Hibernation Mode (NSHM), with the spacecraft spending many days in a special low activity mode, during which the gyroscopes and reaction wheels were inactive and the attitude was controlled by the star tracker and thrusters only. This hibernation capability was required in order to enable the spacecraft to operate with minimal hardware for periods of up to six months during the long 'quiet cruise' phases, with ground contact typically taking place just once per month.

The next major event, which had been added to the original mission timeline, was the monitoring of the after-effects of a collision between a projectile fired from NASA's Deep Impact spacecraft and the nucleus of Comet 9P/Tempel 1.

At NASA's request, Rosetta's initiation of quiet cruising was postponed by several months to enable it to observe the collision from a viewpoint about 80 million km from the comet, with an angle of 90 degrees between the Sun and the comet. On 28 June, the spacecraft slewed to point its four remote sensing instruments at the comet. At 05:52 UT on 4 July, the 362 kg copper projectile smashed into the nucleus at high speed.

ALICE, MIRO and OSIRIS operated continuously from 29 June to 14 July, using a complex pointing profile designed to ensure that the best scientific data were returned from each of the instruments. VIRTIS was operated only for a few hours around the predicted time of impact. Rosetta downlinked an average of 60 Mbytes of scientific data every day to the New Norcia ground station.

OSIRIS observed the nucleus and coma of the comet both prior to and after the impact, using different filters to study the extensive dust cloud that resulted. By measuring the water vapor content and the cross-section of the dust cloud, scientists calculated that some 4,500 tonnes of water were blasted into space by the impact, and, rather surprisingly, that even more dust was ejected (see Fig. 7.8).

The results indicated that comets are composed more of dust held together by ice, rather than being ice contaminated with dust. They are more like 'icy dirtballs' than the 'dirty snowballs' previously believed (see Chapter 1). The scientists did not find evidence of enhanced activity from Comet 9P/Tempel 1 in the ensuing days, suggesting that, in general, impacts with small bodies are not the cause of prolonged cometary outbursts.

The observation campaign was very successful, with all four instruments operating very well. Some problems occurred with the timing of commands for OSIRIS, and with MIRO, but both instruments were recovered within 24 hours, with minor impact on the overall operations and data return.

This exercise was the first scientific planning and operations scenario on a large scale and an extended period of time for the Rosetta mission. It provided an important learning experience that would assist in designing future operations.

With the conclusion of the Deep Impact scientific operations, Rosetta slewed to the Near Sun Hibernation Mode entry attitude on 25 July, and the next day the Passive Cruise Mode was entered, including transition to NSHM and configuration of all subsystems for the new mode. This was the first operational use of this mode, and the intention was to employ it for most of the rest of the journey to Mars.

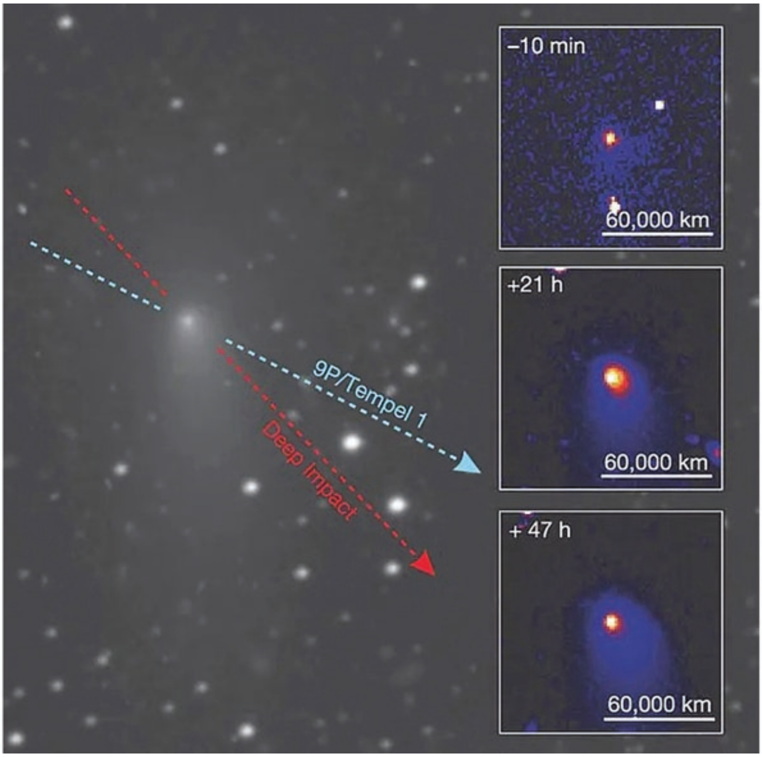

Fig. 7.8: Images taken by the OSIRIS-NAC on Rosetta show the expanding dust cloud that resulted from the collision between Deep Impact's copper projectile and Comet Tempel 1 on 4 July 2005. The dotted lines indicate the projected orbits of the comet (blue) and the Deep Impact spacecraft (red) from the vantage point of Rosetta. The insets show the dust coma and the expanding debris cloud around the time of impact, +21 hours, and +47 hours. The Sun is to the top. A scale line is also included. The outward flow of the impact debris was estimated from the expansion rate of the cloud to be up to 300 m/s. (Kuppers et al, Nature, 13 October 2005)

The spacecraft was to remain in this low activity, low bit rate mode for the next two months, but this changed when an unexpected fuel over-consumption of 20 grams and an unexpected delta-V of 2.5 mm per second were spotted off-line in data that was obtained on 4 August.

An unplanned tracking pass on 8 August provided spacecraft telemetry that indicated that the fuel consumption had returned to normal and the acceleration had disappeared. Nevertheless, analysis of earlier telemetry confirmed that anomalous spacecraft behavior had occurred at the start of August, so it was decided to return to Active Cruise Mode as soon as possible. This transition was completed on 19 August, when the spacecraft was reconfigured to employ the high-gain antenna in X-band for maximum telemetry bit rates. As a safety measure, mission controllers once again began monitoring the spacecraft on a weekly basis.

Another major unexpected event was a solar flare on 8-9 September that hit Rosetta at the beginning of the weekly non-coverage period. When the signal was acquired for the weekly contact on 15 September, mission control found that the spacecraft's active star tracker had crashed, and the second star tracker (not used for attitude control) was in standby mode.

For that time, Rosetta had been relying only on the attitude and orbit control system (AOCS) to determine its attitude using just its gyroscopes, which resulted in a drift of about 0.7 degrees and a small offset in the pointing of the high-gain antenna. Nevertheless, it remained possible to maintain a radio link with Earth.

Recovery activities were implemented immediately and, by the end of that day's ground station pass, both star trackers were in tracking mode and the attitude was restored. Later checks verified that no long-term damage had been caused by the solar flare. It was decided to leave the radiation environment monitor (SREM) on for the long journey out to Mars when Rosetta resumed Passive Cruise Mode.

Rosetta was then used to support a tracking campaign for the validation of the new ESA deep space ground station in Cebreros, Spain. Three passes were conducted successfully on 26, 27 and 28 September.

Apart from regular monitoring and minor maintenance activities, there were few interruptions to this 'quiet' routine. Attitude guidance was changed to +X Earth-pointing on 14 December 2005 in order to minimize the disturbance torques experienced by the spacecraft and the fuel which was then consumed in offloading the reaction wheels. Contact with the spacecraft was via weekly New Norcia passes.

On 10-12 March 2006, Rosetta turned to aim its OSIRIS imaging instrument towards asteroid Steins, its final opportunity to observe the asteroid prior to the fly-by in September 2008. The images collected over a period of about 24 hours were downlinked to Earth on 15-16 March. Although the brightness of the asteroid was comparable to that of a candle from a distance of about 2,000 km, OSIRIS was able to measure variations with an accuracy of better than 2%.

The 'light curve' for Steins implied a spin period of slightly over six hours, in agreement with previous Earth-based studies. The asymmetry of the curve suggested an irregular shape, but OSIRIS found no evidence for either a 'tumbling' motion of the asteroid or the presence of a satellite. By combining the OSIRIS observations with ground-based data, scientists attempted to determine the orientation of the spin axis.

On 15 March, the spacecraft was configured for the first solar conjunction of the mission, in preparation for when it would pass very close to the Sun in the sky, as viewed from Earth. In practice, this meant that its angular distance from the Sun would be less than 5 degrees from mid-March to mid-May 2006, with the minimum of about one third of a degree on 13 April. Such conjunctions cause major communication problems between a spacecraft and its ground stations. To accommodate the significant degradation of the uplink and downlink, the level of activity on the spacecraft was minimized and the S-band transmitter was used in parallel with the nominal X-band link.

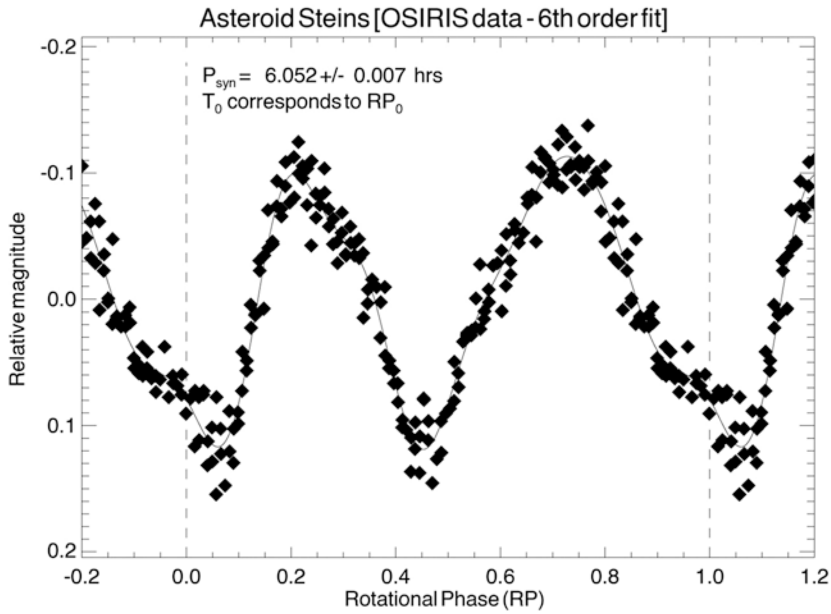

Fig. 7.9: The OSIRIS instrument measured the 'light curve' of asteroid Steins, showing its variation in brightness over one day. The light curve is ~23% brighter at maximum than at minimum. The asymmetry of the curve suggested an irregular shape. One rotation lasted slightly over six hours. (Stefano Mottola/DLR, OSIRIS team)

On 30 March, the telemetry bit-rate was reduced, as planned, to 3.5 kbps in order to help deal with the worsening signal disturbance from the Sun. On 6 April, a telecommand link test was successfully performed and all commands successfully decoded on board, although the uplink signal received by the spacecraft was significantly affected by the Sun.

To measure the performance of the communications link during the solar conjunction (and to support studies of the solar corona) daily ground station passes were initiated, although most of the New Norcia passes were brief (4 hours) and only for tracking, without establishing any telemetry or telecommand connections. The stored telemetry was downlinked when Rosetta emerged from solar conjunction.

On 24 May, Rosetta resumed the Near Sun Hibernation Mode attitude that it was to maintain until the Mars fly-by.

The RPC suite of instruments was activated on 4 July for five days, as Rosetta crossed the tail of Comet Honda. The science observations were stored until they could be downloaded at the next opportunity in August. Preliminary analysis of the data indicated that the magnetometer had been able to detect the tail far downstream from the nucleus. As a result, such campaigns were requested for further potential crossings of comet tails.

7.7 MARS FLY-BY

On 26 July 2006, Rosetta was reconfigured to Active Near Sun Cruise Mode. This meant the spacecraft resumed two ground station passes per week for telemetry recovery and spacecraft maintenance operations.

The Mars Swing-by Phase formally started on 28 July. The fourth passive payload checkout took place in the second half of August, when all instruments except GIADA and ROSINA were activated and checked out in sequence.

Rosetta's second Deep Space Maneuver (DSM2) was made successfully on 29 September, with a delta-V of 31.791 m/s and an overall burn duration of about 52 minutes. The maneuver was performed without ground contact – the high-gain antenna could not be kept pointing at the Earth during the burn because it coincided with the plume zone of the thrusters. The high-gain antenna was moved away shortly before the start of the maneuver, then pointed back after it was completed.

The instruments remained off as various spacecraft checks were completed, notably the fifth AOCS checkout that took place between 11 and 13 October.

Another trajectory correction was carried out on 13 November, a modest delta-V of 9.9 cm/s to improve the accuracy of the Mars approach path.

Meanwhile, preparations got underway for the fourth Active Payload Checkout (PC4). The checkout operations for most of the instruments – except ROSINA and OSIRIS – started on 23 November. The two NAVCAMs were also operated during this slot. All of the checkout operations were executed successfully, apart from several minor glitches that were analyzed and rectified. By December, during the last series of instrument checkouts, the OSIRIS-WAC was able to take long exposure images of the fast approaching planet against the background of stars in which the planet was overexposed and surrounded by a halo of scattered light.

On 3-4 January 2007, the new year's activities began with OSIRIS observations of Lutetia, the second of the mission's asteroid targets. During this 36 hour campaign, a series of images were taken from a range of 245 million km.

On 9 February, 16 days ahead of closest approach to Mars, another small trajectory correction maneuver (TCM-16d) was made which lasted 54 seconds and consumed 58.28 g of fuel. All was now ready for the fly-by of the Red Planet.

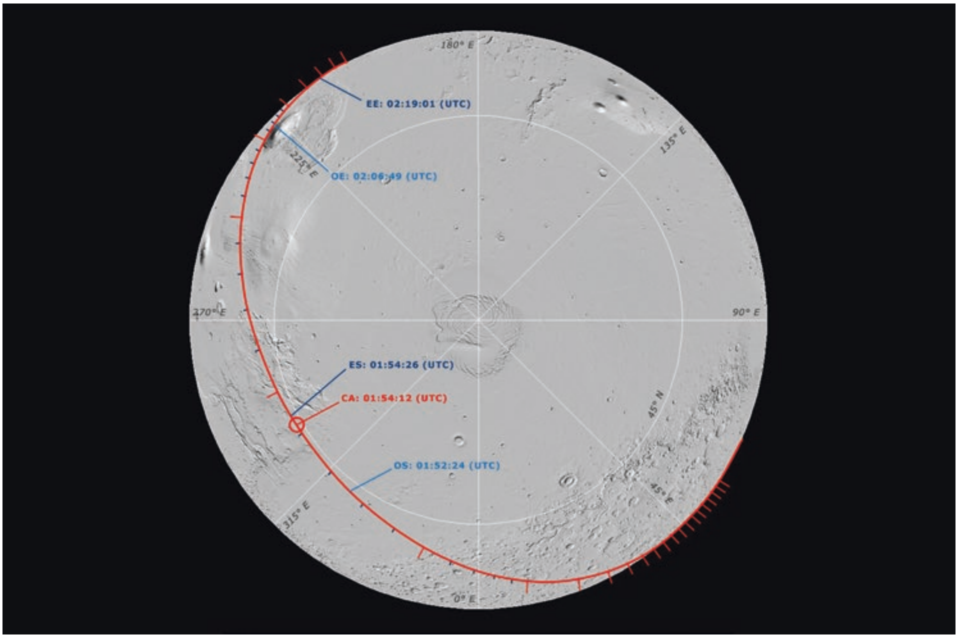

Fig. 7.10: A view of Mars's northern hemisphere showing the ground trace of Rosetta during the fly-by on 25 February 2007. The spacecraft's track around closest approach is projected onto Mars for the period between 23:49:29 UT on 24 February (lower right) and 02:30:48 UT on 25 February (upper left). Red ticks indicate 5 minute intervals, with the smaller dark ticks denoting intervals of 1 minute. Also indicated, with their nominal times are: OS (Occultation Start) – Rosetta behind Mars as seen from Earth; CA (Closest Approach) ~250 km above the surface. ES (Eclipse Start) – Rosetta enters Mars's shadow; OE (Occultation End) – Rosetta observable from Earth again; and EE (Eclipse End) – Rosetta exits the planet's shadow. The closest point of approach was above 43.5° N, 298.2° E. (ESA)

The X-band transmitter was switched off at 01:08 UT on 25 February, and telemetry was lost for almost 90 minutes. However, the S-band carrier signal was still received until 01:56 UT, when ground controllers lost contact for a 15 minute radio blackout as the spacecraft passed behind the planet with respect to ground stations on Earth.

At 01:57:59 UT, Rosetta made its closest approach, passing 250.6 km above 43.5° N, 298.2° E. The occultation (eclipse) started at 01:58 UT, with the spacecraft spending about 25 minutes in shadow. Tension was high in the mission control room until the S-band carrier signal returned on time, signifying Rosetta had powered up again successfully upon re-emerging into sunlight.

Rosetta passed over the planet's surface at a relative speed of 36,191 km/h. During the swing-by, the gravitational pull of Mars caused Rosetta to change direction, placing it on course for its second encounter with Earth in November 2007. The spacecraft was decelerated by an estimated 7,887 km/h relative to the Sun, putting it in the desired 0.78 × 1.59 AU orbit inclined 1.9 degrees to the ecliptic.

During the approach to Mars, SREM, the standard radiation monitor, observed the radiation environment for 48 hours and its RPC plasma suite spent 48 hours measuring the properties of the charged particles and the magnetic field along the trajectory.

The OSIRIS camera system captured a series of images of Mars and the small moon Phobos as it emerged from behind the planet and transited the Martian disk. These were later assembled into a movie.

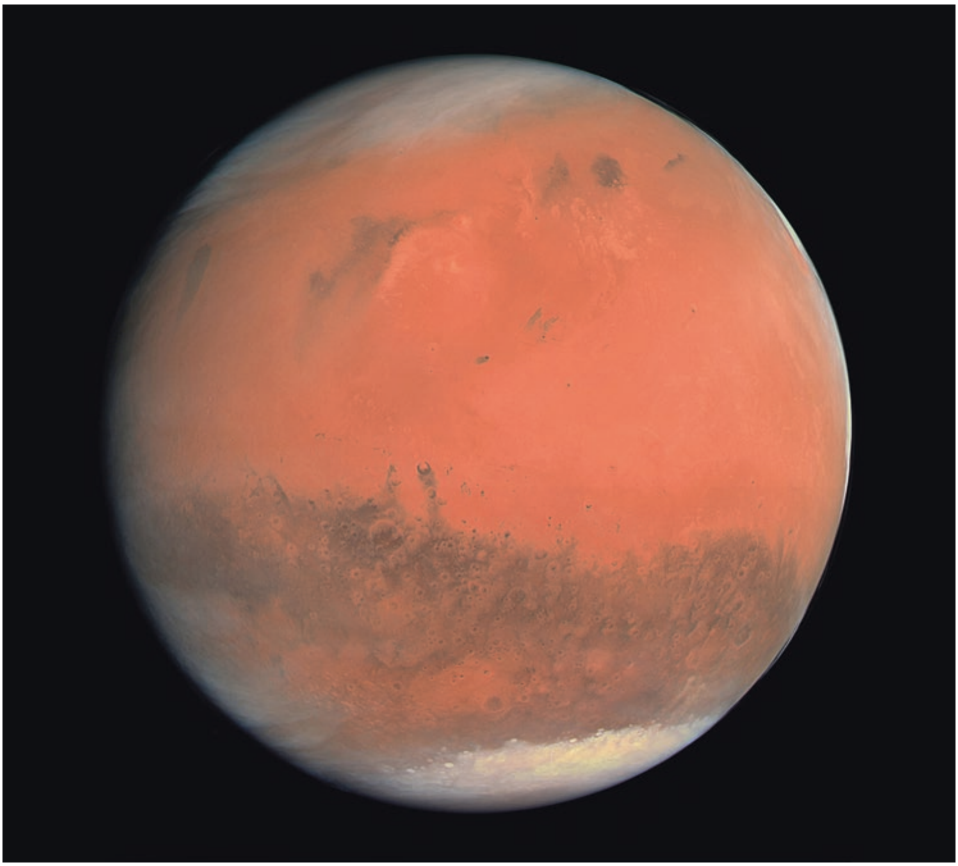

Fig. 7.11: An OSIRIS-NAC true color view of Mars taken at 18:28 UT on 24 February at a distance of 240,000 km, about 7.5 hours before closest approach to the planet. It combines images obtained with orange (red), green, and blue filters. The spatial resolution is about 5 km per pixel. The greenish areas are clouds. The south polar ice cap is clearly visible. The image is centered on the red desert of Elysium Planitia. (ESA & MPS for OSIRIS Team MPS/UPD/LAM/IAA/RSSD/INTA/UPM/DASP/IDA, CC BY-SA 3.0 IGO)

Some magnificent full disk images of Mars were returned, showing the south polar cap, ice clouds in the northern polar region, and sparse morning clouds. Above one limb, the images provided an edge-on view of clouds some 50-60 km above the surface. Stereoscopic images were also obtained.

The fly-by was during the southern spring, a time of the Martian year when a large amount of carbon dioxide and water ice is vaporizing from the southern polar cap, prior to migrating to the northern polar cap during northern winter.

VIRTIS also studied Mars at infrared wavelengths and, together with ALICE, performed a spectroscopic analysis of the atmosphere. NAVCAM images were also obtained.

Because the upper atmosphere of Mars is similar to the ultraviolet spectrum of a comet (in that it is dominated by carbon monoxide, hydrogen, carbon, and oxygen, as well as their ions) this was the first opportunity for ALICE, the ultraviolet imaging spectrometer, to function in something that resembled a comet's environment.

It saw the sunlit upper atmosphere emitting ultraviolet light, thus providing the first in-situ observation of this 'dayglow' phenomenon on Mars. Such observations can give important information on how carbon dioxide, the principal gas in the planet's atmosphere, behaves at high altitude. ALICE also mapped the night side spectrum, studying the far ultraviolet 'nightglow' and seeking evidence of auroras. In addition, OSIRIS and ALICE searched for a dust ring above the equator.

Rosetta switched off its solar-powered instruments prior to executing the fly-by, because its path would take it through the shadow of Mars. Without sunlight, the instruments would have had to draw power from the batteries – which had to be husbanded for exploring Comet 67P. The fly-by trajectory also imposed a loss of communication during an occultation with Earth, starting 2 minutes prior to closest approach and lasted about 15 minutes.

Passing through the planet's shadow was an unfortunate consequence of re-targeting Rosetta at 67P, rather than 46P/Wirtanen, with different launch and fly-by timings. The mission team improvised a means of obtaining data anyway, by turning on two instruments on the battery-powered Philae lander – which operated independently of Rosetta for a total of three hours, including the eclipse. The ÇIVA camera took images of Rosetta in silhouette against the red-brown surface of Mars (see Fig. 7.12), and the Rosetta Magnetometer and Plasma monitor (ROMAP) observed the patchy magnetic field of the planet and the turbulence caused as the solar wind crossed the 'bow shock' upstream of it (see Fig. 7.13).

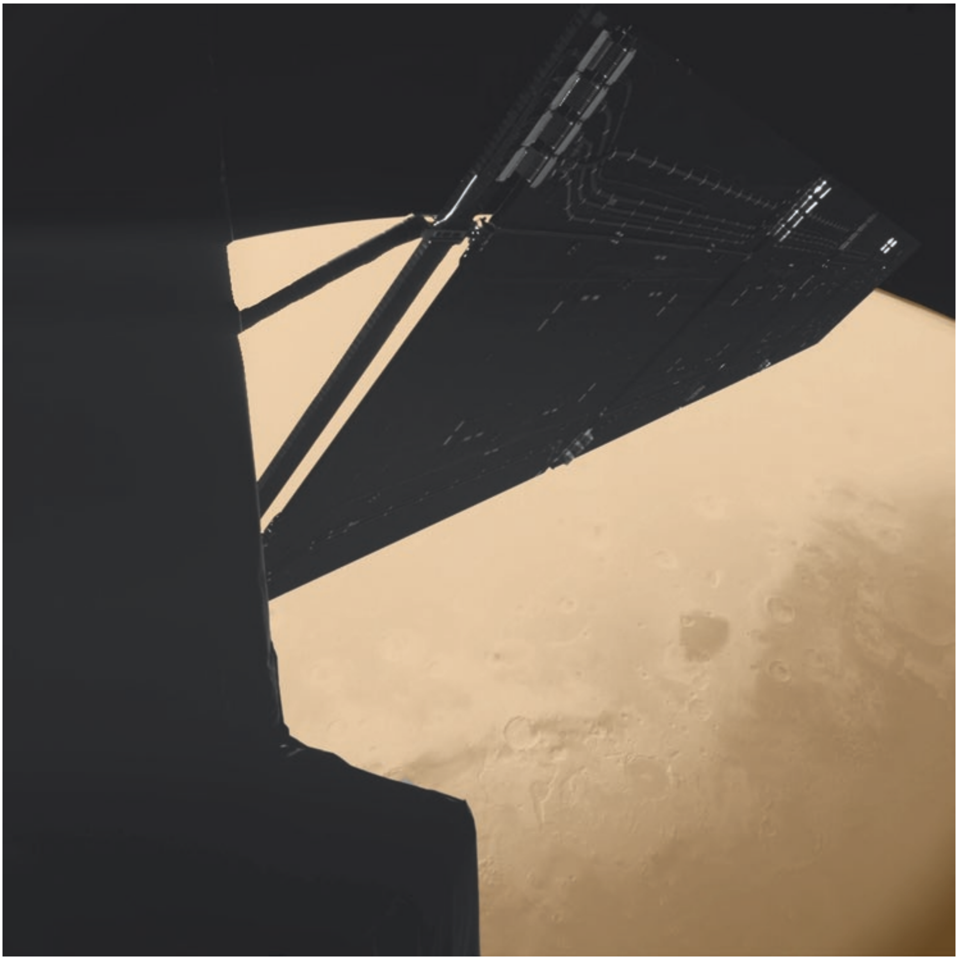

Fig. 7.12: This image was taken by the ÇIVA imager on the Philae lander during the Mars swing-by on 25 February 2007, four minutes before closest approach at a distance of about 1,000 km. It shows part of the main spacecraft and one of its solar arrays, with Mars in the background. The lander was attached to the side of the main spacecraft. (ÇIVA/Philae/ESA Rosetta)

The downlink of the science data acquired during the fly-by was completed on 9 March. The Mars Swing-by Phase was formally wrapped up by the third Deep Space Maneuver (DSM3) on 26 April, a minor adjustment that consumed ~6.96 kg of fuel and altered the spacecraft's velocity by 6.526 m/s. The departure trajectory took the spacecraft through the magnetotail of the planet.

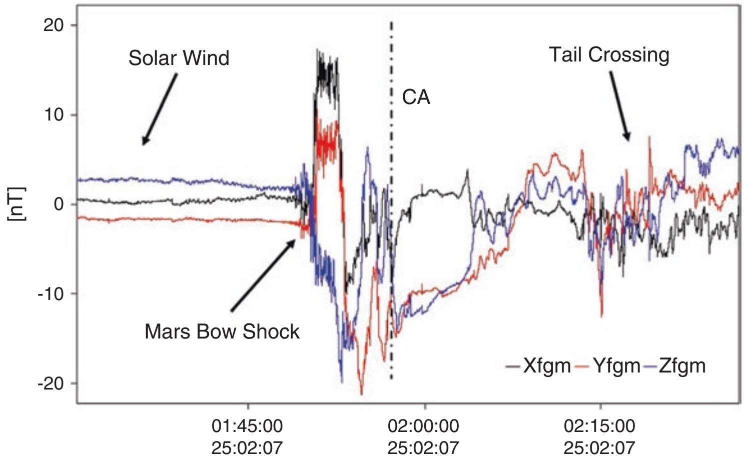

Fig. 7.13: This data from the ROMAP instrument on the Philae lander shows the magnetic environment around Mars. The incoming supersonic solar wind is undisturbed (left) until it encounters the boundary 'bow shock' of the magnetosphere, after which it is decelerated to subsonic speed and becomes turbulent. The horizontal axis shows time and the vertical axis shows the intensity of the magnetic field. (ROMAP/Philae/ESA Rosetta)

7.8 EARTH FLY-BY #2

Having left Mars behind, Rosetta turned its instruments toward Jupiter, the largest planet in the Solar System. At extremely long range, ALICE watched as NASA's New Horizons flew down the Jovian magnetotail, bound for distant Pluto. The instrument also observed Jupiter's auroras and the plasma torus created by its volcanically active moon Io. These observations were completed on 9 May.

Although Jupiter was just a pinprick of light, ALICE was able to separate its emitted light into the three components that made up its spectrum. These included sunlight reflected from Jupiter's cloud tops, ultraviolet emission given off by particles ejected in eruptions from the volcanoes on Io, and light from auroras caused by particles striking the planet's atmosphere – some from the Sun and some ejected from Io.

Rosetta passed the aphelion of its third orbit around the Sun on 20 May 2007, when it reached a heliocentric distance of 237.14 million km (1.58518 AU). After its fifth passive payload checkout, the spacecraft was again placed into Near Sun Hibernation Mode on 5 June, a quiet phase that was punctuated by weekly ground contacts. In early September, the spacecraft was reconfigured back to Active Cruise Mode, followed by a month of active payload checkout 6, starting on 17 September.

As Rosetta was rapidly approaching Earth for the second time, controllers chose to refine its path with a trajectory correction maneuver on 18 October that lasted for 46 seconds and gave a delta-V of 3.4 cm/s.

At 20:57:23 UT on 13 November 2007, the mission made its second Earth swing-by, with the closest point of approach 5,295 km above the Pacific Ocean (63.76° S, 74.58° W), south-west of Chile, at a relative velocity of 45,000 km/h (12.5 km/s).

On this occasion, the highest priority was given to spacecraft operations because the gravity assist was crucial for the success of the overall mission. In any case, on both the inbound and outbound tracks the solar illumination and temperature conditions were rather unfavorable. As a result, there were very limited time slots available for the instruments to be used safely.

Nevertheless, some instruments were activated for calibration, scientific measurements and imaging. These observations were scheduled during and around the time of closest approach, from 7 to 20 November.

Observations were made by the navigation cameras, the ALICE ultraviolet spectrometer, the OSIRIS cameras, and the VIRTIS infrared instrument. ALICE was used to obtain spectra of the illuminated Earth and Moon. VIRTIS studied fluorescent emission of carbon dioxide and molecular oxygen by scanning the atmosphere whilst pointing at the limb on the sunset side. VIRTIS also obtained spectra of the Moon.

The MIRO microwave instrument was also activated several times during the fly-by phase in preparation for the observations which were planned for asteroids Steins and Lutetia. And the ROMAP magnetometer and plasma monitor on the Philae lander was operative for about two weeks.

The SREM radiation monitor made measurements of Earth's radiation belts, and the Radio Science Experiment provided tracking data to investigate possible anomalous accelerations during swing-bys.

During its approach, OSIRIS captured images of Earth's night side, showing large cities that appeared as points of light, along with a narrow crescent of light above the South Pole. After closest approach, the instrument's NAC was able to image both Earth and Moon. The results included color views of Earth's daylight hemisphere, featuring Australia and south-east Asia, and the Earth-facing side of the Moon.

Rosetta first pointed toward Earth in order to perform observations of the atmosphere and the magnetosphere – including a search for shooting stars from space. It imaged urban regions in Asia, Africa and Europe, then aimed at the Moon and obtained spectra of its illuminated face. After closest approach to Earth, the spacecraft looked back and its NAVCAM took a series of black-and-white images that included Antarctica and a crescent Moon.

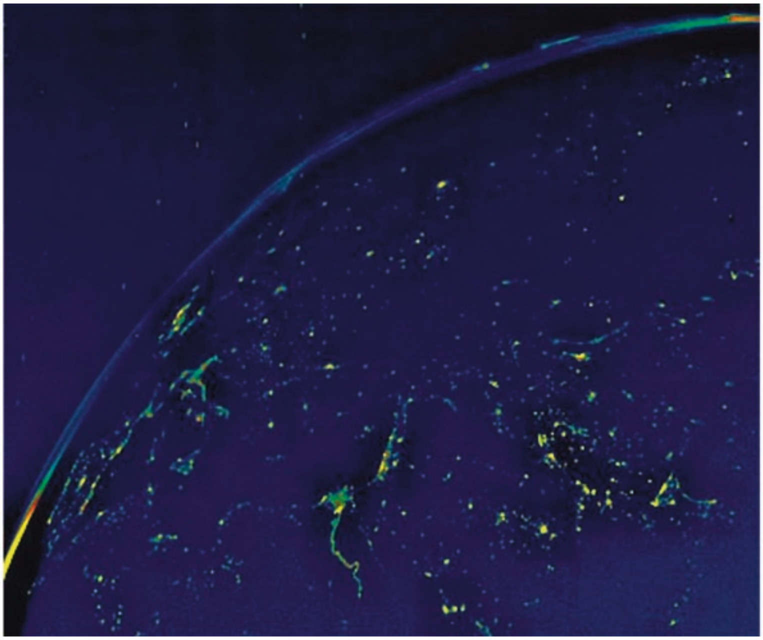

Fig. 7.14: During its second approach to Earth, Rosetta observed the planet's night side. This OSIRIS-WAC image was taken with a red filter at 19:30 UT on 13 November 2007. Its false colors highlight city lights in Europe, north Africa and the Middle East. (ESA ©2005 MPS for OSIRIS Team MPS/UPD/LAM/IAA/RSSD/INTA/UPM/DASP/IDA)

Rosetta observed the Moon for 11 hours shortly after the Earth fly-by, and then, as it receded, it performed observations of the Earth-Moon system on 15, 16, 18 and 20 November.

Additional passes using ground stations of the NASA's Deep Space Network were used to download the science data from the fly-by as rapidly as possible. The Santiago Station was used to cover the periods of closest approach that could not be covered using ESA's ground stations, in order to obtain a full set of data that might record any indications of a possible anomalous acceleration that had been reported at previous close Earth gravity assist manoeuvres (see Box 7.2: The Mystery of the Fly-by Anomaly). No effect was detected this time.

The second Earth fly-by helped Rosetta to gain sufficient energy to be catapulted towards the main asteroid belt, where it was to investigate the small asteroid, Steins, in September 2008. By this stage, Europe's comet chaser had flown a little over 3 billion km of its 7.1 billion km journey toward 67/P Churyumov-Gerasimenko.

Fig. 7.15: After its second Earth gravity assist, Rosetta looked back and took a number of images. This OSIRIS-NAC image was taken at 02:30 UT on 15 November 2007, and is a composition of orange, green and blue filters. The continent of Australia is evident at the bottom. (ESA ©2007 MPS for OSIRIS Team MPS/UPD/LAM/IAA/RSSD/INTA/UPM/ DASP/IDA)

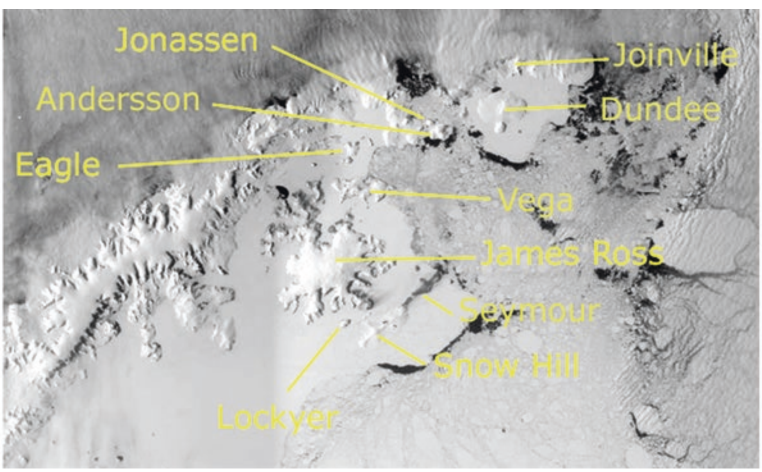

Fig. 7.16: An image by one of Rosetta's NAVCAMs on 13 November 2007 from an altitude of 5,350 km. Graham Land is the portion of the Antarctic peninsula that lies closest to South America. Various nearby islands are labeled. (ESA)

7.9 STEINS

After swinging by Earth on 13 November, Rosetta's operations focused on downlinking the science data, spacecraft reconfiguration and checkout activities, and, based on tracking during daily passes with the New Norcia ground station, correcting its trajectory.

The first of two planned TCMs to put Rosetta on course for Steins took place at 00:54 UT on 23 November. The maneuver was executed using onboard accelerometers, and lasted 538 seconds. The velocity change (delta-V) was 1.526107 m/s and the estimated total fuel consumed was 1.6 kg.

At perihelion on 17 December at about 136 million km (0.91077 AU) from the Sun, Rosetta was largely shut down. It started its fourth orbit around the Sun with a passive payload checkout (PC7) in early January 2008, and observations were made of the portion of sky that would be seen during the approach to asteroid Steins.

On 21 February, the second planned TCM prior to the Steins encounter was completed, with a tiny velocity change of 248.3 mm/s.

The next major activity was a test of the asteroid fly-by attitude dynamics on 24 March. This validated the spacecraft's behavior under the extremely dynamic conditions imposed by the fly-by scenario chosen for Steins. It was also an opportunity to test the behavior of the AOCS software in Asteroid Fly-by Mode (AFM), the influence of stray sunlight on the star trackers of the orbiter, and the cameras of the orbiter and lander.

Three days later, Rosetta adopted Near Sun Hibernation Mode attitude to cruise passively with its gyros switched off and attitude control relying on thrusters. It was not reactivated until 1 July, after which it was reconfigured once more to Active Cruise Mode.

The eighth active payload checkout (PC8) involved conducting a series of commissioning activities and software updates for the instruments over a period of four consecutive weeks. In parallel, the eighth attitude and orbit control system checkout was conducted.

The Steins navigation campaign got underway in early August, with long range imaging on 4, 7, 11, 14, 18, 21, and 25-31 August and 1-4 September. From mid-August the spacecraft was pointing permanently at the asteroid, apart from occasional re-alignments for instrument calibrations. This was the first time in the history of ESA spacecraft operations that such a technique had been used. Of the total of 324 observations by NAVCAM and OSIRIS-NAC, 75 were taken by OSIRIS.

The accuracy of the earlier measurements exceeded expectations, enabling them to be used for the execution of the first trajectory correction maneuver on 14 August. Designated CA-3 (Closest Approach Minus 3 Weeks), the 113 second maneuver changed Rosetta's velocity by 12.8 cm/s and adjusted its trajectory to open its closest approach to Steins from 554.2 km out to 792.4 km, very near the 800 km which would provide the best fly-by conditions consistent with spacecraft performance.

The CA-8d slot for trajectory correction on 28 August, eight days before closest approach, was not used. However, it was necessary to refine the orbit with an additional TCM on 4 September, around 36 hours before closest approach, in order to achieve the desired flyby conditions.

The CA-36h maneuver lasted for 103.5 seconds and consumed 127.1 g of fuel. The resultant velocity change was 11.8 cm/s, ensuring that Rosetta's estimated closest approach would take place at an ideal altitude of 800.7 km.

Scientific activities associated with the fly-by began on 20 August, when the OSIRIS camera completed another observation of the asteroid's light curve.

The fly-by was to occur on the sunlit side of Steins to facilitate continuous observation of the asteroid before, during, and after closest approach – while passing through a phase angle of zero (with the Sun directly overhead). To keep the small object in the field of view of the scientific instruments in the closest approach phase, the spacecraft would have to be aimed with an accuracy of better than 2 km.

It was also programmed to perform an attitude flip maneuver that would last for 20 minutes, starting 40 minutes prior to closest approach (see Fig. 7.17). Rosetta had to change its orientation rapidly, pushing the system to its design limits during the high speed fly past.

During this autonomous tracking of the asteroid, the attitude of the spacecraft was automatically driven by NAVCAM A in order to keep the small asteroid continuously in the field of view of the imaging instruments. A rehearsal in March 2008 had not gone quite to plan.

As operations manager Sylvain Lodiot explained:

> The NAVCAMs were not behaving as expected and the 12 hours leading up to the Steins fly-by were spent trying to find proper settings for them. For both cameras the tracking data delivered was not satisfactory for the enabling of the autonomous tracking mode. The background noise was disturbing the measurements and delivering a distorted set of data.
>
> The control team spent many hours finding a set of parameters that could allow the camera to deliver proper data. The final configuration was reached some tens of minutes before the fly-by itself. Those hours were pretty stressful. Even then, some spacecraft off-pointing was observed during the AFM mode, with Steins sometimes drifting out of view. Significant work had to be done to improve the technique before the fly-by of Lutetia.

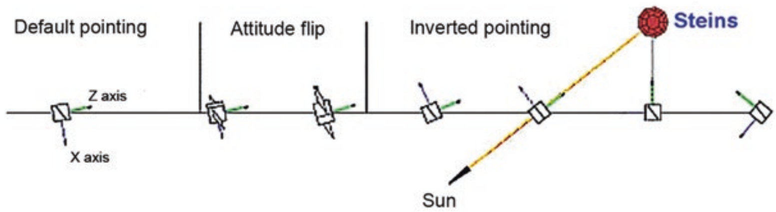

Fig. 7.17: A schematic illustrating Rosetta's attitude flip and autonomous pointing during the fly-by of Steins, with time running from left to right and the spacecraft's attitude indicated by its +Z axis (toward asteroid Steins, red) and +X axis (blue). (ESA)

As it closed in, Rosetta turned its high-gain antenna away from Earth, breaking the telemetry signal, and initiated its scientific observations.

The closest approach to Steins was at 18:38:19 UT on 5 September 2008, some 2.14 AU from the Sun and 2.41 AU from Earth. The spacecraft swept past the asteroid at a relative velocity of 8.62 km/s (about 31,000 km/h).

Fourteen instruments were switched on for the fly-by, providing detailed, multi-wavelength analyses of the asteroid and in-situ measurements of its dust, plasma, magnetic and radiation environment.

The remote sensing instruments – ALICE, OSIRIS, VIRTIS and MIRO – provided imaging and/or spectrometry at ultraviolet, visible, infrared, and submillimeter wavelengths. Both the OSIRIS cameras were used. The NAC was expected to obtain the highest resolution images, but unfortunately it ceased its programmed observations at a distance of 5,200 km from the asteroid and entered safe mode about 10 minutes prior to closest approach. Consequently, the highest resolution images, at about 80 meters per pixel, were taken by the WAC from a range of about 800 km around the time of closest approach (see Fig. 7.18).

The five instruments of the Rosetta Plasma Consortium – IES, ICA, LAP, MIP, MAG – as well as ROMAP and SREM, sensed the charged particle, magnetic and radiation environment near the asteroid. The ROSINA and GIADA instruments searched for gas and dust around it. Instruments on the lander were also operating, as was the Radio Science Experiment.

The Rosetta control room at the European Space Operations Center, Darmstadt, received the first radio signal via NASA's Goldstone antenna at 20:14 UT, confirming that the spacecraft was performing is programmed operations. Activities continued for several days after closest approach, including gravitational microlensing observations by OSIRIS. All the science data acquired during the asteroid fly-by were downlinked by the beginning of October, interleaved with OSIRIS science observations.

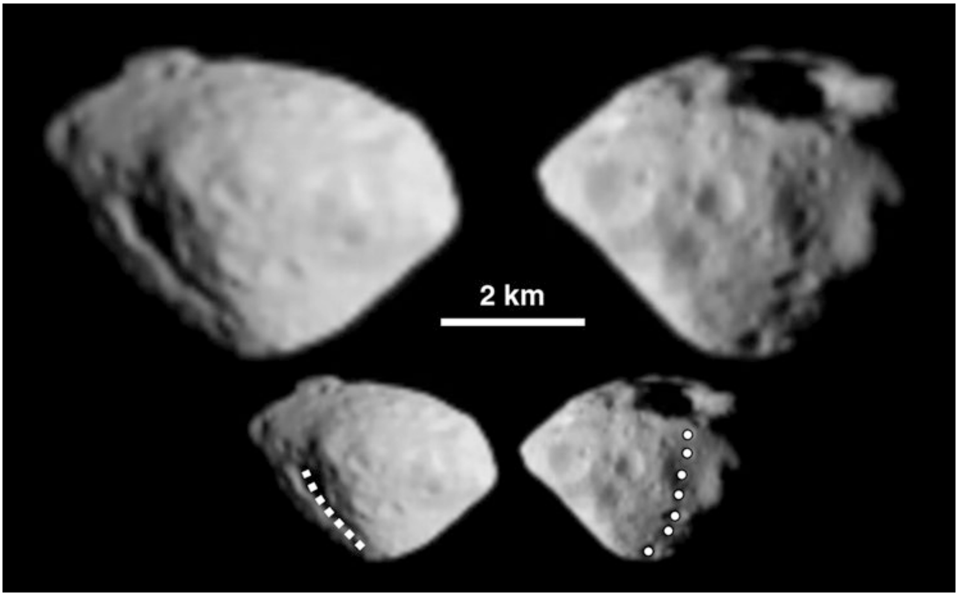

Fig. 7.18: Images of Steins taken by the Wide Angle Camera and Narrow Angle Camera of OSIRIS. The WAC image (top right), taken around closest approach, shows the surface at a resolution of 80 meters per pixel. The NAC image (top left) taken 10 minutes before closest approach, has a resolution of 100 meters per pixel. The scale is given by the 2 km bar. The difference in line of sight between the images is 91 degrees and they give two views of the asteroid. Steins's rotation is retrograde (east to west) and therefore, in accordance with IAU rules, its north pole points towards celestial south. As a result the large, 2 km diameter crater is close to the south pole. The positions of the seven pits in the linear catena (bottom right image) and the large fault on the opposite side (bottom left image) are indicated. (ESA © 2008 MPS for OSIRIS Team MPS/UPD/LAM/IAA/RSSD/INTA/UPM/DASP/IDA)

Up to that time, seven asteroids had been encountered by spacecraft: five S-type (stony), one V-type (Vestoid) and one C-type (carbonaceous) (see Chapter 1). Asteroid (2867) Steins was the first of the rare E-type to be visited by a robotic explorer, so scientists were eager to learn more about its characteristics to improve their knowledge of the variety of asteroids, and how the Solar System formed and evolved. The surface composition of E-type asteroids resembles that of enstatite achondrite meteorites (having a high content of magnesium silicate) but their origin is uncertain. E-types are the dominant asteroids in the Hungaria group in the main belt between Mars and Jupiter.

Rosetta confirmed that the rotation period of Steins is roughly 6 hours, and found that it spins in a retrograde (east to west) direction, so its north pole faced toward celestial south.[1] The fact that the north-south axis of rotation was roughly perpendicular to the orbital plane meant the spacecraft flew right over its equator. OSIRIS imaged about 60% of the surface, revealing the asteroid to be shaped like a diamond with dimensions 6.67 × 5.81 × 4.47 km, widest at its equator.

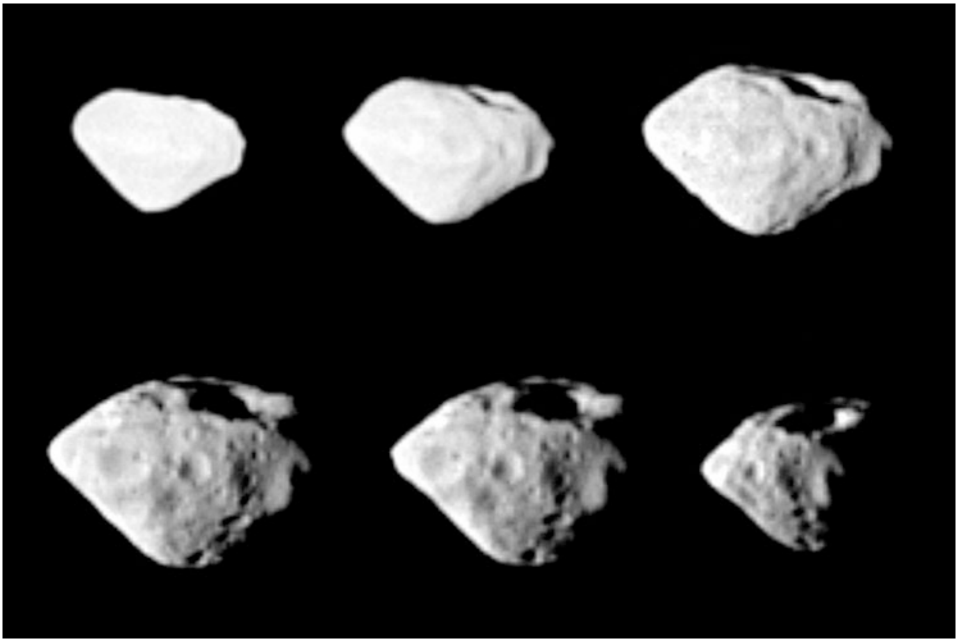

Fig. 7.19: OSIRIS-WAC images of Steins taken during the 5 September 2008 fly-by. *(ESA ©2008 MPS for OSIRIS Team MPS/UPD/LAM/IAA/RSSD/INTA/UPM/DASP/IDA)*

Compared with other asteroids imaged at close quarters by spacecraft, Steins has a low crater density, and almost all of them are shallow indentations. The overall crater shape and depth-to-diameter ratio are consistent with degradation (or infill) by material ejected from impacts and disturbance of loose regolith (surface material) by seismic shaking during large impacts.

Nevertheless, the ancient surface has at least 40 small, shallow impact craters and two larger ones (see Fig. 7.20). The largest, just over 2 km in diameter and nearly 300 meters deep, is at the south pole. It was named Diamond, in reference to the asteroid's overall shape. A linear chain of similarly sized hollows, called a catena,

[1] Many objects in the Solar System, such as Earth, rotate from west to east, so that their north pole points toward celestial north. However, some objects, such as Steins, spin in a backward or retrograde direction (east to west) and, in accordance with the rules of the International Astronomical Union (IAU), their north pole points toward celestial south.

extends north from it and crosses the equator (see Fig. 7.18). It may have been created by the excavation of Diamond opening a subsurface fracture, into which loose material later settled, creating hollows. On the opposite side of the asteroid is a large groove (fracture or fault) that stretches from the north pole to the equator.

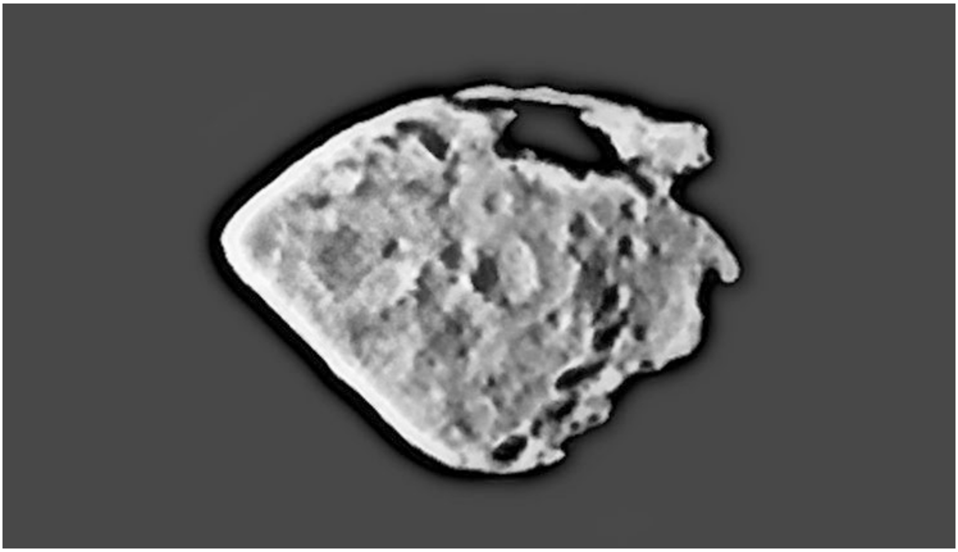

Fig. 7.20: Steins imaged by Rosetta's OSIRIS camera on 5 September 2008. Image stacking and processing by amateur astrophotographer Ted Stryk enhanced the shadows to emphasize the difference between bright crater rims and their shadowed floors. Over 40 craters can be discerned on the surface. The largest shown at the top of this frame is the 2 km wide crater named Diamond, which is actually at the south pole. (ESA ©2008 MPS for OSIRIS Team MPS/UPD/LAM/IAA/RSSD/INTA/UPM/DASP/IDA; processing by T. Stryk)

The explosive creation of Diamond was probably one of the major contributors to the general appearance of the asteroid. The fracturing would have given rise to a loosely bound 'rubble pile' which had a low overall density. Furthermore, debris from the impact would have been scattered across the surface, masking older craters.

Scientists believe that Steins was originally part of a larger, differentiated object which broke up long ago. It was then battered by impacts, most significantly by the creation of Diamond. Its unconsolidated nature suggests that a major collision in the future could easily shatter it into fragments.

Analysis of the data by the OSIRIS principal investigator Horst Uwe Keller, and colleagues, attributed the striking conical appearance of Steins and the relatively low number of craters with diameters of less than 0.5 km to surface reshaping as a result of the Yarkovsky-O'Keefe-Radzievskii-Paddack (YORP) effect. This was the first time that this effect had been seen in a main belt asteroid.

The YORP effect is a phenomenon that occurs when light photons from the Sun are absorbed by a small body and re-radiated as infrared emission. This carries away momentum as well as heat. Because more heat escapes from one side of the object than the other, its rate of rotation (and possibly its spin axis) will change.

If the rate of spin slowly increases, loose material may slide toward the equator. Landslides, or gradual movement of granular material and small boulders, could have erased many of the smaller craters and made the distinctive conical shape. However, if this was once the case, the current rotation rate of Steins is too slow for the YORP effect to further modify it. Seismic tremors generated by small objects striking the surface would have further disturbed the loose material.

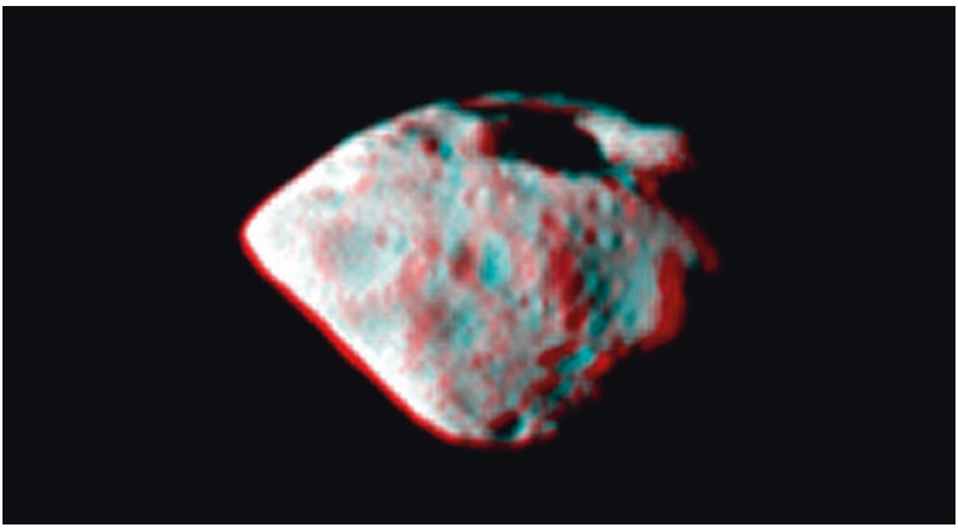

Fig. 7.21: Asteroid Steins in 3D. This image, which gives a visual impression of the highs and lows of the surface, is based on data collected by Rosetta at a distance of about 800 km. It is best viewed using stereoscopic glasses with red-green or red-blue filters. (ESA ©2008 MPS for OSIRIS Team MPS/UPD/LAM/IAA/RSSD/INTA/UPM/DASP/IDA)

Detailed analysis of the OSIRIS images allowed Keller and his colleagues to confirm that the fairly high albedo (reflectivity) and spectral characteristics of Steins are consistent with its classification as an E-type asteroid. The low iron content and lack of measurable variation in surface color were evidence of a homogeneous composition.

Box 7.1: Naming Features on Steins

Following analysis of the images returned by Rosetta's OSIRIS cameras, a number of distinct surface features were identified and named on asteroid Steins. Because its shape bears some resemblance to a cut diamond, the International Astronomical Union (IAU), which decides on the official place names given to all worlds in the Solar System, accepted a proposal from the OSIRIS imaging team that craters on Steins be named after gemstones.

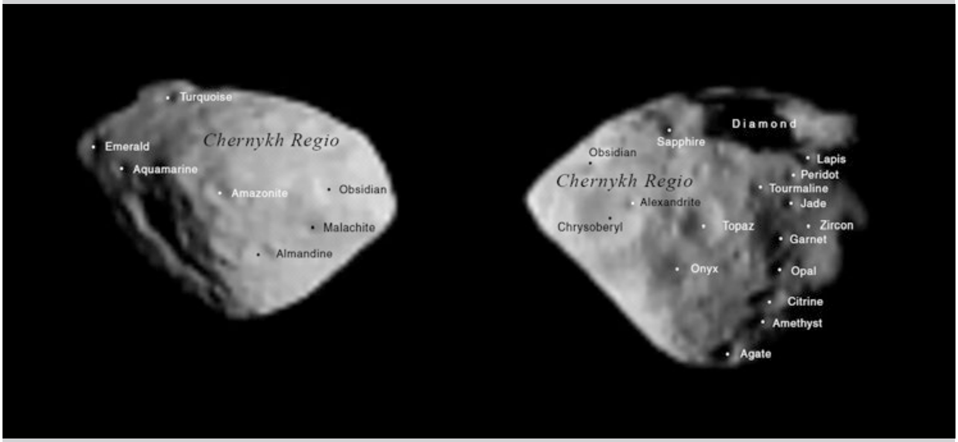

Fig. 7.22: Named features on asteroid (2867) Steins. (©ESA 2012 MPS for OSIRIS Team MPS/UPD/LAM/IAA/RSSD/INTA/UPM/DASP/IDA)

The process of naming major features on Steins was initiated by Sebastien Besse, a PhD student working with the OSIRIS imaging team in France, who went on to become a Research Fellow at ESA-ESTEC in the Netherlands.

During his studies of the craters on Steins, he began to think about a suitable nomenclature for them. Since Steins looks very much like a diamond, he decided to research the names of different gemstones, with a view to linking them to particular craters. One of the factors influencing his deliberations was a desire to select names that would be familiar or appealing to the general public, and relatively easy to pronounce.

After discussions with the rest of the team, it was agreed that the names of 23 gemstones or precious minerals would be recommended to the IAU. At the same time, it was decided to follow tradition by naming a large region after the asteroid's discoverer, Nikolai Chernykh, who first detected Steins in 1969. Although the name 'Ruby' was rejected as unsuitable and replaced by 'Diamond', most of the names were officially accepted in May 2012.

The name Diamond was assigned to the dominant landform, a 2.1 km diameter impact feature near the south pole. A circular crater about 650 meters wide and 80 meters deep that was imaged in the center of the asteroid during closest approach was called Topaz.

Another notable feature is a catena, a chain of pits (or crater-like hollows) that stretches from the asteroid's north pole all the way to Diamond crater. At least some of the craters in the chain may have been formed by loose material sinking into a subsurface fracture. These were named after familiar gemstones such as Agate, Opal and Jade. However, Besse also decided to include Citrine, since it sounds like the French word for lemon: citron.

Another elongated feature (a groove or fault), surrounded by small pits and craters, is visible on the other side of Steins, approximately opposite to the catena. This feature has yet to be named.

7.10 BACK TO EARTH

As tiny Steins was left behind, Rosetta continued its passage through the inner asteroid belt. With almost all of the instruments shut down, the top priority of the two weeks that followed the encounter was to downlink the science data. All of the measurements acquired during the fly-by were successfully received on the ground.

For four weeks following the fly-by, the only noteworthy scientific operations were periodic observations of gravitational microlensing events in the Galactic Bulge using the OSIRIS Narrow Angle Camera. This was one of several serendipitous science research programs that were added to the main scientific program during Rosetta's cruise phase.

Gravitational microlensing occurs when a massive object passes in front of a fainter object. The gravity of the foreground object serves as a lens, bending the light from the more distant star or planet, giving rise to two or more distorted, unresolved images which are noticeably magnified.

In practice, because the required alignment is so precise and difficult to predict, microlensing is very rare; hence the decision to view the densely populated center of our Galaxy. Starting on 7 September and continuing until 4 October, a series of seven observations were made. It was expected that observations of the dense star fields would include about 50 microlensing events at any one time. When compared with simultaneous observations taken with ground-based telescopes, it was expected the observations would provide accurate masses for dozens of stars and other faint objects, in particular 'failed stars' known as brown dwarfs and perhaps a couple of exoplanets.

For five days in October and November when mission activity was low, engineering teams investigated an issue that had occurred with the COSIMA instrument during the Steins fly-by. After settling on the instrument's Target Manipulation Unit (TMU), it was decided to upload software updates as part of the active payload checkout scheduled for September 2009.

During the latest active cruise phase, all instruments were once again switched off, except for the SREM radiation monitor that ran in the background.

On 17 December, Rosetta passed the aphelion of its current orbit around the Sun, reaching a record distance of 338.63 million km (2.26 AU). Eight days later, its distance from Earth set a new record for the mission at 485.12 million km (3.24 AU).

Meanwhile, between 17 December 2008 and 6 January 2009, Rosetta was within 3 degrees of the Sun as viewed from Earth, with the minimum separation on 27 December.

As the new year dawned, the spacecraft was given its ninth passive payload checkout with the instruments being activated and checked one at a time. In addition, various maintenance tasks were carried out.

On 16-18 February, while still near aphelion, a thermal characterization exercise was carried out to verify the thermal performance of the spacecraft and its instruments in preparation for the fly-by of asteroid Lutetia in July 2010, which would occur at 2.7 AU. It was conducted by exposing the spacecraft to the Sun with an elongation angle of first +175 degrees from the +Z axis (positive towards the +X axis) and later +192 degrees. Each attitude was maintained for 24 hours, sufficient to attain thermal stabilization. There were no problems in sustaining these attitudes.

However, some problems were noted with the ROSINA and the VIRTIS instruments, which reported non-ideal conditions when going to 192 degrees, exposing the rear of the spacecraft to the Sun. ROSINA noted outgassing that could disturb its asteroid measurements, obliging the ground team to favor early exposure of the back side of the spacecraft for the instrument. VIRTIS recorded high sensor temperatures that were likely to impair its science results. This could be obviated by limiting the exposure of the rear of the spacecraft to very short times. These factors would be taken into account when the mission team eventually defined the final operational requirements for the Lutetia fly-by.

Several recovery activities, test activities, and software updates were also performed, with the troublesome Target Manipulation Unit on COSIMA being fully recovered.

7.11 EARTH FLY-BY #3

The fourth Deep Space Maneuver (DSM4) was successfully performed on 18 March, slightly modifying the trajectory in preparation for Rosetta's third swing-by of Earth on 13 November 2009.

After a short tracking campaign to define the new orbit, the active cruise phase was replaced by passive cruise phase #6 on 2 April. With all of the instruments switched off apart from the SREM, the spacecraft was once again placed in Near Sun Hibernation Mode, where it would remain until 8 September. Weekly monitoring was conducted via ESA's New Norcia ground station.

On 9 September, the telemetry, tracking & commanding was reconfigured from the medium-gain antenna to the high-gain antenna, and the next day the tenth spacecraft checkout (SC10) started. This activity was briefly interrupted on 16 September by the spacecraft entering safe mode, but it was soon recovered and the checks were successfully completed. The tenth payload checkout (PC10) started on 17 September and finished on 8 October. It involved the staggered activation, testing and calibration of the instruments, as well as software updates.

In the first half of October, the mission team checked out the readiness of ESA's Kourou and Maspalomas ground stations, as well as the NASA Deep Space Network stations at Canberra, Madrid and Goldstone, using X-band and S-band radio frequencies. The navigation campaign leading to the Earth fly-by started with data about Rosetta's inbound trajectory provided by its telemetry, and from Doppler and ranging data received from the ESA and NASA ground stations. Based on this data, the flight dynamics team was able to calculate any changes to the spacecraft's velocity that might be required to refine the approach to Earth.

The primary trajectory correction was conducted on 22 October, three weeks prior to closest approach. The four axial thrusters fired for 86 seconds to achieve a delta-V of 8.8 cm/s. The accuracy of this maneuver meant that no further corrections would be necessary.

A safe mode was triggered on 5 November, as Sylvain Lodiot's operations team was trying to send commands to Rosetta to retrieve lost data from its memory. Fortunately, the spacecraft was soon returned to normal. Nevertheless, Lodiot carried out an analysis of the unexpected shut down, and realized there had been many similar close calls during previous data dumps. From then on, therefore, the operations team made sure never to attempt to redump lost data.

On 6 November, ALICE was switched on as part of the scientific operations planned during the Earth swing-by. This enabled researchers to test ALICE's performance by viewing Earth in ultraviolet light. The spectral data confirmed that the instrument was in focus, and showed the main ultraviolet spectral emission of our planet. MIRO, OSIRIS, RPC and VIRTIS were activated during the next few days. The encounter program would span more than a week on either side of closest approach.

Between 8 and 18 November, when not conflicting with the swing-by mission operations, the spacecraft slewed as necessary to make observations of Earth and the Moon. In addition, the various science teams used the opportunity to

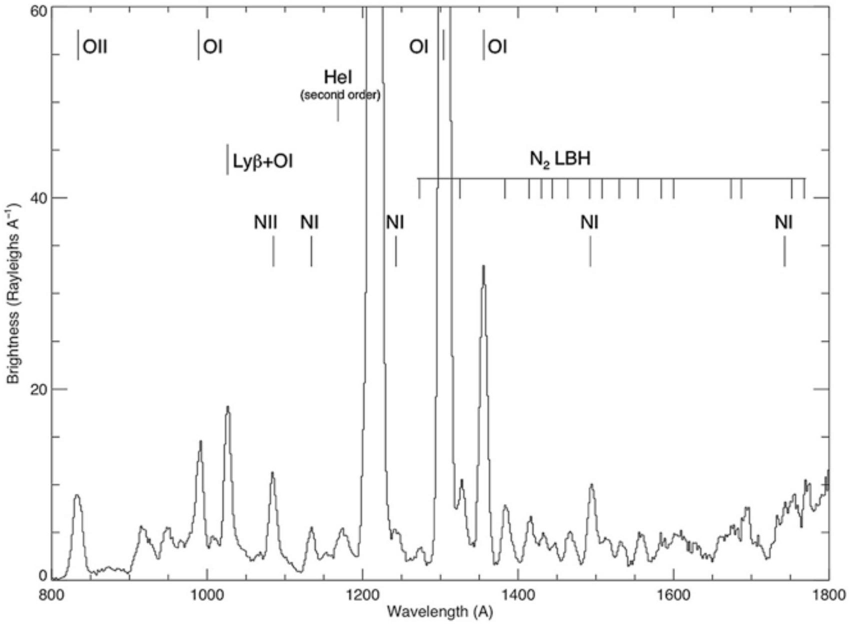

Fig. 7.23: A graph showing one of the spectra obtained by the ALICE ultraviolet instrument during the approach to Earth. Some of the oxygen (O) and nitrogen (N) emission lines have been labeled. (NASA/JPL/SwRI)

characterize the performance and calibrate their instruments in preparation for the program intended for the encounter with asteroid Lutetia in 2010 and, ultimately, with Comet 67P in 2014.

Rosetta's final visit to Earth was achieved at 07:45:40 UT on 13 November, with the closest point of approach 2,479.523 km being above the Indian Ocean, south of the Indonesian island of Java. The gravity assist meant that the spacecraft received a boost of 3.6 km/s, accelerating it into a new orbit with an aphelion at about 5.33 AU and a perihelion still bound to 1 AU.

Mission operations were primarily conducted by ESA's New Norcia ground station, with the support of tracking passes by Kourou in French Guiana and Maspalomas in Spain, as well as by NASA's DSN stations at Goldstone (DSS-24), Madrid (DSS-54) and Canberra (DSS-34). The success of the swing-by was confirmed when contact was established via Maspalomas at 08:05 UT.

All the science observations during the swing-by were successfully performed. In addition to imaging Earth and the Moon, OSIRIS sought auroras, lunar sodium and a hydroxyl (OH) tail during lunar stray light calibration.

Fig. 7.24: This image was obtained as Rosetta approached Earth for the third swing-by. It was acquired with the OSIRIS-NAC from 633,000 km at 12:28 UT on 12 November 2009, with a resolution of 12 km per pixel. The crescent is roughly centered on the South Pole. The outline of Antarctica is visible under the clouds which form the south polar vortex. Very bright spots are strong reflections from pack ice along the coastline. (ESA ©2009 MPS for OSIRIS Team MPS/UPD/LAM/IAA/RSSD/INTA/UPM/DASP/IDA)

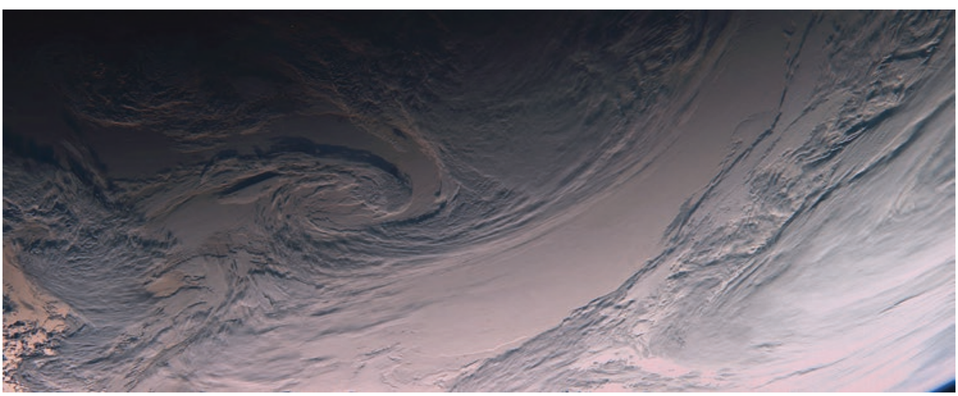

Fig. 7.25: A high-resolution view of the South Pacific by the OSIRIS-NAC on 13 November. The image shows cloud structures associated with an anticyclone. This false-color composite was generated using the orange, green and blue filters. (ESA ©2009 MPS for OSIRIS Team MPS/UPD/LAM/IAA/RSSD/INTA/UPM/DASP/IDA)

Fig. 7.26: This OSIRIS image of the USA at night from a distance of 60,000 km was taken with a 10 second exposure on 13 November 2009 at 04:44 UT, three hours prior to closest approach. The bright spots show the cities on the east coast and the Gulf of Mexico. Some cities are clearly visible, but others like New York are covered by clouds, making the light diffuse. (ESA © 2009 MPS for OSIRIS-Team MPS/UPD/LAM/IAA/RSSD/INTA/UPM/ DASP/IDA)

During its approach to Earth, Rosetta took a sequence of full-disk images of the night side using the VIRTIS Mapper channel (VIRTIS-M). This hyperspectral imager collected image data simultaneously in 864 narrow, adjacent spectral bands (colors) from distances ranging between 240,000 and 228,000 km. When the spacecraft was less than 55,000 km from Earth, it carried out limb scans of the night side, starting from 150 km above the surface. Between 14:00 and 14:25 UT on 13 November, the instrument looked back at Earth from 230,000 km and studied the composition of the observed areas. Combining the images with spectral data enabled two-dimensional compositional maps to be created (see Fig. 7.27).

The results confirmed the ability of VIRTIS to isolate desired features of the observed object, using the spectral data. They included color composites of Earth composed by using different spectral bands in the visual wavelength range. One false-color image revealed the distribution of chlorophyll, a key signature of vegetation, in the South American rainforest. Other images showed Earth in the infrared.

The SREM instrument was used to determine the spatial distribution of Earth's radiation belts along the spacecraft's trajectory. The data included count rates for electrons and protons, the strength of the magnetic field, and the derived electron fluxes in different energy ranges.

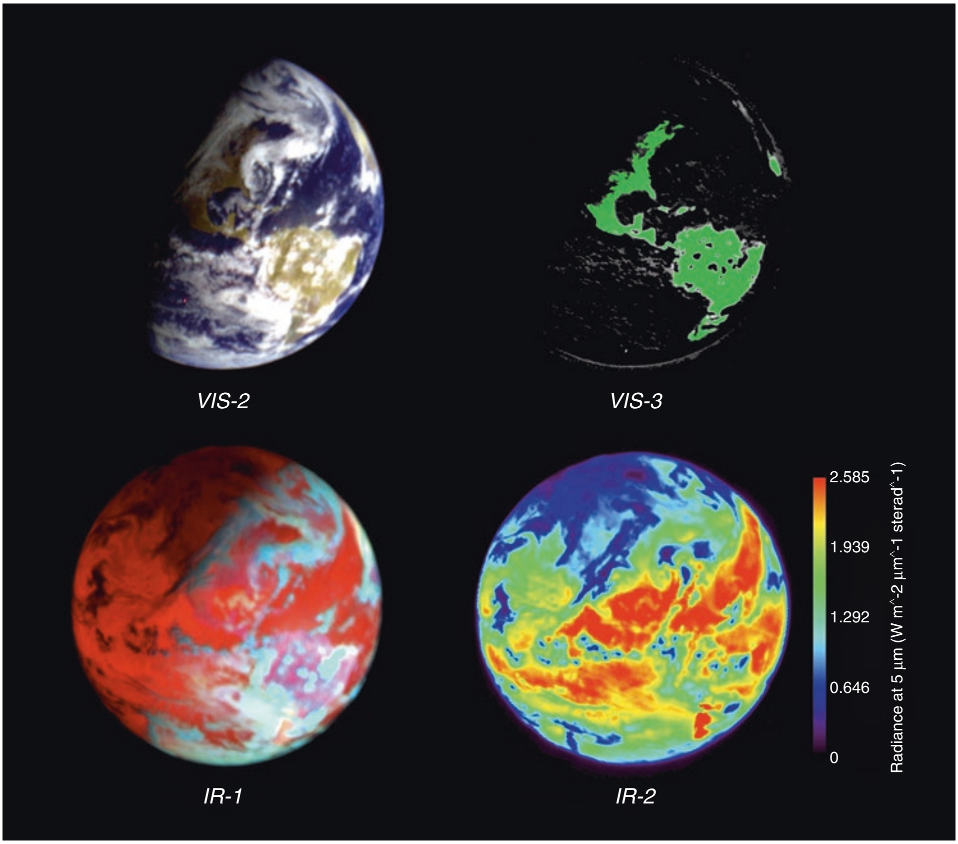

Fig. 7.27: A selection of VIRTIS imagery from the final Earth fly-by. VIS-2 was obtained over the Gulf of Mexico and the Americas at 14:00 UT on 13 November, in the visible and near-infrared spectral range with a spatial resolution of about 50 km. The western coast of Africa can also be seen at the top right of the image. The blue, green and red channels were selected to provide maximum contrast to the ground, clouds and sea: 0.474 micrometers for sea water, 0.785 micrometers and 1.0 micrometers for land. The VIS-3 image was obtained several hours after closest approach, about 230,000 km from Earth. The composite image shows the distribution of the chlorophyll present in vegetation, with maximum chlorophyll abundance shown in green. Black patches over parts of South America are caused by dense clouds which completely masked the ground. IR-1 is an infrared view of Earth using colors with the R, G and B channels at 4.92 micrometers, 2.25 micrometers and 1.20 micrometers respectively. Being sensitive to reflected solar radiation and emitted thermal radiation, the VIRTIS-M data allowed the night side to be seen. The cyan areas are related to high altitude clouds, which are particularly bright in the near-infrared on the day side. Landforms appear pink. IR-2 was obtained using thermal emission at 5.0 micrometers. The color scale (right) shows the measured radiance. The warmest areas (orange-red) are on the day side and in the equatorial region. The coldest areas (violet) are the tops of the clouds and the region (upper left) that includes Canada and the Arctic. (INAF-IFSI/INAF-IASF/ASI)

Starting at 20:00 UT on 9 November, the RPC suite of five instruments made complementary measurements of Earth's plasma environment and magnetospheric studies for a week around closest approach. On 10 November, its Langmuir Probe (LAP) detected clear signals from the spacecraft firing its thrusters.

A clean-up maneuver with a delta-V of 58 cm/s was performed on 23 November to eliminate an inaccuracy in the departure trajectory. Rosetta was now on course to re-enter the asteroid belt, but still five years away from its historic rendezvous with Comet 67P.

Box 7.2: The Mystery of the Fly-by Anomaly

Since NASA's Galileo spacecraft experienced a speed increase of 3.9 mm/s greater than expected when it swung past Earth in December 1990, mission controllers and scientists at ESA and NASA have noticed that some spacecraft experience unexpected changes in speed during Earth fly-bys. This appears to be due to a strange variation in the amount of orbital energy they exchange with Earth.

The changes in speed are extremely small and may occur as either an increase or a decrease in velocity. However, attempts to explain and predict the variation by means of fundamental physics have all failed.

The largest unexpected variation – a boost of 13.0 mm/s – was observed when NASA's NEAR spacecraft made its Earth swing-by in January 1998.

Scientists were hoping to gain more insight into the anomaly when Rosetta swung by Earth on three separate occasions. Curiously, the spacecraft had an unexplained velocity increase of 1.8 mm/s during the first fly-by in 2005, but no evidence for the mysterious variation was detected in either 2007 or 2009.

"It's a mystery as to what is happening with these gravity events," said Trevor Morley, lead flight dynamics specialist working on Rosetta. "Some studies have looked for answers in new interpretations of current physics. If this proves correct, it would be absolutely ground-breaking news."

Attempted explanations range from tidal effects of the near-Earth environment, atmospheric drag, or the pressure of radiation emitted or reflected by the Earth, to much more extreme possibilities, such as dark matter, dark energy, or previously unseen variations in General Relativity.

One American research team, led by ex-NASA scientist John Anderson, has even looked at the possibility that Earth's rotation may be distorting space-time – the fundamental fabric of our Universe – more than theory predicts, and affecting spacecraft, but there is, as yet, no explanation for this mechanism, and why it should occur during some fly-bys and not others.

Before even considering such exotic explanations, all the usual causes of spacecraft speed errors have been thoroughly eliminated by numerous investigations at both ESA and NASA. Software bugs, calculation errors, tracking uncertainties and other, much more mundane causes have all been systematically eliminated or accounted for, leaving the speed anomaly maddeningly unexplained. The mystery remains!

7.12 BACK TO THE ASTEROID BELT

On 23 November, Rosetta passed through the perihelion of its current orbit, at 146.6 million km (0.98 AU) from the Sun. It would never again be within the radius of Earth's orbit around the Sun.

Apart from the SREM radiation monitor, which continued to run in the background, all of the instruments were off.

The new year, 2010, began inauspiciously, with Rosetta entering an unplanned safe mode on 1 January, in the middle of a week that was between ground communication passes. It proved to be an issue with one of the remote terminal units. After further investigation on 4 January, the spacecraft was restored to normal operations over the next three passes.

On 11 January, a test was successfully completed to characterize the telecommand link performance on the low-gain antenna, using both the ESA New Norcia ground station and a NASA DSN ground station at Goldstone. This cleared the way for a test of the Deep Space Hibernation Mode (DSHM), the never-before-tried operating mode which the spacecraft was to employ between June 2011 and January 2014, during its passive cruise to Comet 67P.

The aim of the test was to validate the spacecraft behavior and the operational scenario for the hibernation phase, including:

- The spacecraft configuration for DSHM entry.
- The spacecraft spin-up maneuver.
- Detection and processing of Rosetta's strobing signal on the ground.
- Commanding hibernation entry.
- The spacecraft in DSHM configuration for 1 week.
- The spacecraft's autonomous DSHM exit.
- The spacecraft spin-down.
- Recovery of the spacecraft after DSHM exit.

The DSHM test was successfully completed between 20 and 27 January. During this period, the largely dormant spacecraft was monitored daily for about 8 hours.

Rosetta was spin-stabilized on 20 January (rather than the normal three-axis stabilization) and commanded to enter hibernation mode the next morning. After the spin-up, the downlink was alternated several times between modulated telemetry using the medium-gain antenna and an unmodulated carrier signal using the high-gain antenna to monitor the systems and to test the signal acquisition of the 'strobing' pulses from the spinning spacecraft, respectively.

After DSHM began, the spacecraft switched off the subsystems for attitude and orbit control (AOCS) and for telemetry, tracking and command (TTC). The TX-2 transmitter was switched on again later for monitoring purposes during the test.

At the start of the week-long test, the spin rate was commanded to 4 degrees per second (or two-thirds of a revolution per minute). Data showed that it decreased very slowly over time, at a rate of about 0.0002 degrees per second per day, presumably because of solar radiation pressure acting on the large solar arrays and the high-gain antenna dish. The principal inertial axis, or spin axis, which had been estimated beforehand to be at about 7 degrees in the +X/+Z quadrant of the spacecraft's reference frame, shifted to 10.4 degrees.

Throughout the DSHM test, spacecraft temperatures remained within limits, and it was not necessary for the mission operations team to intervene.

The hibernation was completed on 27 January as planned, although an autonomous action of the computer caused Rosetta to enter a safe mode. By mid-afternoon, the reaction wheels had resumed attitude control and the spacecraft was once again three-axis stabilized. Another safe mode was triggered during the post-DSHM recovery. However, the spacecraft was promptly restored to its normal operating mode.

The solid-state mass memory, which had been powered down on 21 January and was off for the entire test, was fully re-configured as part of the nominal recovery activities after exiting DSHM.

With Rosetta returned to normal cruise mode, early February saw re-lubrication of reaction wheel B. When the so-called run-in phase was completed on 11 February, it was returned to the control loop of the attitude and orbit control system to enable the spacecraft to use all four reaction wheels. Several payload tests and software updates were also conducted.

Between 14:33 UT and 15:15 UT on 24 February, the solar generator on the Philae lander was tested. Isolated from the Rosetta orbiter in terms of power, the lander drew current from its own battery and solar arrays while being exposed to the Sun.

By now, thoughts were turning to the forthcoming fly-by of asteroid Lutetia. In a rehearsal on 14-15 March, the spacecraft repeated the attitude flip made at Steins and then autonomously tracked a virtual point which corresponded to what would be Lutetia's position.

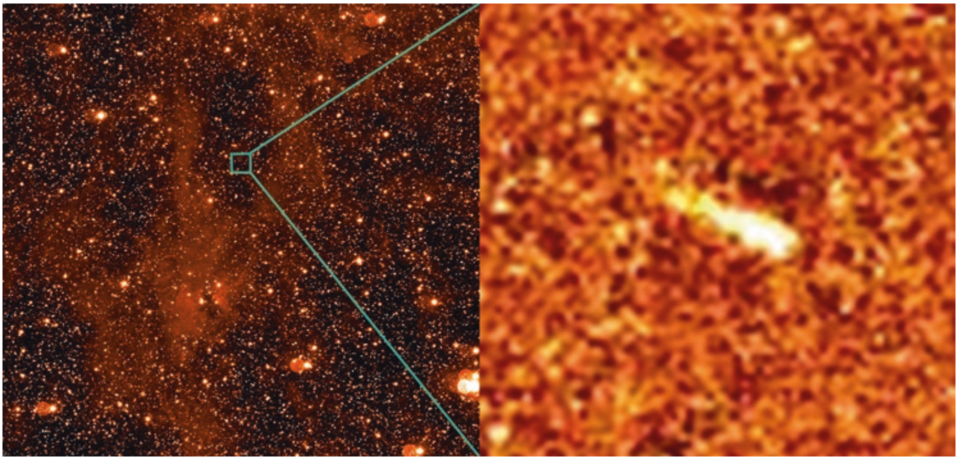

Fig. 7.28: Rosetta image of asteroid P/2010-A2. The OSIRIS-WAC image (left) spans 2.2 × 2.2 degrees; the NAC image (right), spanning 200 × 200 seconds of arc, shows the asteroid and its trail. The halo-like features around the bright stars are internal reflections within the camera. (ESA – OSIRIS-Team; MPS/UPD/LAM/IAA/RSSD/INTA/UPM/DASP/IDA)

On 16 March, the OSIRIS-NAC made observations of the comet-like object P/2010-A2 (see Fig. 7.28) whose position in the inner portion of the asteroid belt, small nucleus and long dust tail suggested it was a member of a group of rare ‘main belt comets’ which were suspected of being icy asteroids undergoing episodes of cometary activity.

Despite its great distance from P/2010-A2, Rosetta’s unique vantage point enabled scientists to see the strange object from a unique perspective. By combining data from ground-based observatories and the Hubble Space Telescope, they were able to reconstruct the three-dimensional shape of P/2010-A2’s diffuse trail in great detail. This confirmed that the object and its apparent tail were actually the remains of an asteroid collision that happened one and a half years earlier.

Three weeks of active payload checkout 12 (PC12) started on 23 April, when most of the instruments were activated for their final check and update prior to the Lutetia fly-by. These activities were successfully completed on 17 May.

Meanwhile, on 14 May, Rosetta flew beyond 2.26 AU, its previous farthest distance from the Sun. By late May, the spacecraft was being tracked regularly by the ESA New Norcia ground station and by NASA DSN stations at Goldstone (DSS-15, DSS-24 and -25), Canberra (DSS-34 and -45) and Madrid (DSS-54, -55, -63 and -65) for radio navigation purposes inbound to Lutetia.

In addition, Rosetta’s cameras began tracking the asteroid for optical navigation. The first set of observations was completed on 31 May, when the spacecraft was 53 million km from its objective. These observations were initially made twice a week, but as the range reduced the rate was increased to daily. They utilized the two navigation cameras (NAVCAM-A and -B) and OSIRIS-NAC. However, OSIRIS remained off on 31 May, owing to low temperatures on the instrument’s electronics box.

The orientation of the spacecraft was adjusted to allow those components to warm up. The camera was activated on 2 June, for use during the remainder of the navigation campaign. On 18 June, the temperature of the CCDs in the NAVCAMs was lowered from –25°C to –30°C in order to reduce the number of 'warm pixels'.

On 11 June, Rosetta's attitude and orbit control system (AOCS) and the telemetry, tracking and commanding (TT&C) subsystem were configured for the fly-by. On 14 June, NASA's 70 meter dish antenna in Madrid (DSS-63) was used to rehearse the fly-by operations, including a change of telemetry bit rate during the pass, with data acquisition in X- and S-band for the RSI experiment.

At about 06:28 UT on 18 June, a minus-3-weeks trajectory correction maneuver (TCM) with a nominal delta-V of 27.5 cm/s was performed to refine the trajectory for Lutetia. By 27 June, the range had reduced to 16.5 million km, and Rosetta was closing in rapidly. One week later, the distance was 7.33 million km and the spacecraft was following a perfect path for its close fly-by.

Box 7.3: Enigmatic Lutetia

As described in Chapter 1, asteroid discoveries were few and far between during the 19th century. Only the largest and brightest of these small, rocky objects could be detected by large ground-based telescopes – in most cases by chance.

Rosetta's main asteroid target, Lutetia, was only the 21st such object to be numbered since the discovery of the first asteroid, Ceres, in 1801. Discovered by Hermann Goldschmidt in Paris in November 1852, it was given the Roman name for the French capital city: Lutetia.

The asteroid follows a fairly normal orbit in the inner asteroid belt, at a mean distance of approximately 2.4 AU, or 364 million km, from the Sun. The orbit lies almost in the plane of all the planets – the ecliptic – and is moderately eccentric (elliptical). Its orbital period is 3.8 years.

Nevertheless, prior to Rosetta's fly-by, Lutetia posed a riddle for planetary scientists. In particular, there was uncertainty about its size, mass, density, composition and origin.

After Lutetia was announced as a target for Rosetta in 2004, it was subjected to intense ground-based scrutiny. These observations enabled astronomers to construct its shape and spin rate from the changing light curve. Most asteroids tend to be irregularly shaped, so that different amounts of light are reflected as they rotate. The ratio between the three major axes of an asteroid, and its rotational properties, can be determined from measuring how this reflected light changes with time. Assuming a certain reflectivity (albedo), the dimensions of the asteroid can also be estimated.

The results indicated Lutetia to be an irregular, cratered body with dimensions of 132 × 101 × 76 km. In addition, the rotational axis of the asteroid is highly inclined and almost in its orbital plane, so that it resembles a spinning top knocked on its side – much like the planet Uranus. This led to the prediction that Rosetta would see only the northern hemisphere, and that the southern hemisphere would be dark and cold during the fly-by.

It was also estimated that Lutetia rotates with a period close to 8.17 hours – knowledge that was of great help in planning the scientific measurements during Rosetta's fly-by.

Initial observations recorded a high albedo, suggesting a high metallic content, and this led to the body being classified as an M-type asteroid. However, the lack of clear features in its light spectrum led some researchers to suggest it more closely resembled a C-type, a form of primitive, carbon-rich object similar in composition to meteorites classified as carbonaceous chondrites.

When Lutetia was at opposition in 2008-2009, the opportunity was taken to test this theory further. A team of researchers used the giant VLT, Keck and Gemini telescopes to estimate that Lutetia has a high bulk density – in the range 3.98 to 5.00 g/cc, depending on the model that was used. This range of density would support a carbonaceous composition. Meanwhile, visual spectroscopic studies noted variations with rotation phase, possibly representing local differences in the mineralogical or chemical content of the surface.

Bearing this in mind, scientists were looking forward to solving the following questions about Lutetia through analysis of Rosetta's fly-by data:

- *What is the asteroid's true composition? Is it a C-type or M-type asteroid?*
- *What are its precise mass and density?*
- *What is its surface topography and geology? What processes have shaped its surface?*
- *When and where did Lutetia originate? As a primitive planetary building block, it could provide important clues about how the inner Solar System formed.*
- *Is it surrounded by an exosphere – an extremely sparse envelope of gases? If so, what is its composition?*

In addition, the fly-by would provide ground-truth to improve the calibration of observations obtained by ground-based telescopes. It would also be a rare opportunity to test the scientific instruments on board Rosetta before it reached its final destination.

7.13 LUTETIA

Rosetta passed by asteroid (21) Lutetia at 15:44:57 UT on 10 July 2010, at a relative speed of 15 km/s and a range of 3,162 km. The asteroid was 2.72 AU (406.9 million km) from the Sun and 3.05 AU (456.2 million km) from Earth, giving a signal travel time of about 20 minutes.

The closest approach phase was followed using the 70 meter dish (DSS-63) at NASA's DSN ground station in Madrid. This allowed the spacecraft to transmit telemetry at the maximum bit rate of 91 kbps. The large dish was also used to amplify the signal as much as possible, in support of the two-way RSI radio link for tracking purposes.

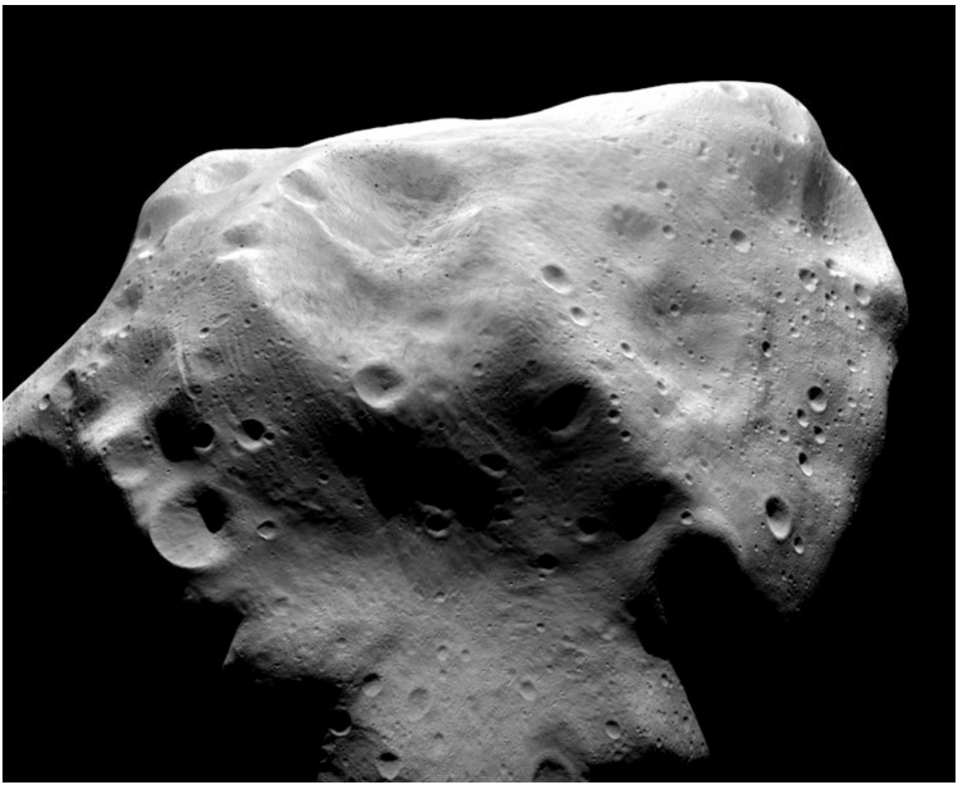

Fig. 7.29: A view of Lutetia provided by OSIRIS during closest approach. The large ridged crater on the left shows numerous dark boulders and landslides. (ESA 2010 MPS for OSIRIS Team MPS/UPD/LAM/IAA/RSSD/INTA/UPM/DASP/IDA)

The fly-by strategy allowed continuous observations before, during, and for 30 minutes after closest approach, at which time the spacecraft had reached the minimum permitted angle with respect to the Sun and had to slew away from the asteroid.

About four hours prior to closest approach, Rosetta performed a flip maneuver to acquire the correct attitude, preparatory to entering Asteroid Fly-by Mode. In this mode, the attitude of the spacecraft was automatically driven by one of the navigation cameras so that Lutetia was continuously in the field of view of the imaging instruments. The flyby was conducted with the spacecraft autonomously tracking the asteroid, as practiced during the March rehearsal.

Seventeen instruments were operated during the encounter, including remote sensing and in-situ measurements and some of the payload of the Philae lander (the main exceptions being CONSERT and GIADA). Together, they looked for evidence of a highly tenuous atmosphere (exosphere) and magnetic effects, as well as studying the asteroid's surface composition and density. They also attempted to capture any dust grains that were floating near the asteroid for onboard analysis. Analysis of the fly-by data provided no significant evidence for it having either an exosphere or an internal magnetic field.

The fact that Lutetia rotated on its side meant that only about half of the asteroid was imaged by OSIRIS – almost the entire northern hemisphere and portions of the southern hemisphere, revealing a cratered, irregular object. At approximately 121 × 101 × 75 km, it was the largest asteroid yet encountered by a spacecraft. Scientists suspect that Lutetia was once more or less spherical, and a battering by incoming objects blasted large amounts of rock from its surface.

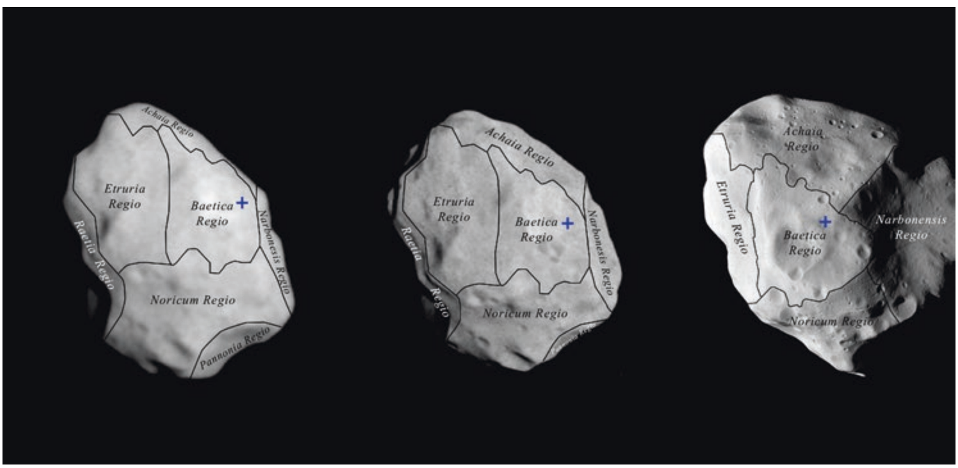

Fig. 7.30: The named regions on asteroid Lutetia. The three images were taken (left to right) 60, 30 and 3 minutes prior to Rosetta's closest approach on 10 July 2010. They were taken at ranges of 53,000, 27,000 and 3,500 km respectively, with spatial resolutions of about 1,000, 500 and 60 meters per pixel. The Rosetta science team identified seven distinct topographic and geological regions, named for provinces of the Roman Empire. The unobserved area of the southern hemisphere was named after Hermann Goldschmidt, who discovered Lutetia in 1852. The blue cross indicates the north pole. (ESA 2010 MPS for OSIRIS Team MPS/UPD/LAM/IAA/RSSD/INTA/UPM/DASP/IDA)

As Rosetta drew close, a giant bowl-shaped depression stretching across much of the asteroid rotated into view. Images showed that some portions of Lutetia are heavily cratered, implying considerable age. Based on crater counts, parts of its surface appear to be about 3.6 billion years old. Areas with few craters suggest a surface age of 50-80 million years old, which is regarded as young by astronomical standards.[2]

The detailed images enabled scientists to identify seven distinct topographic and geological regions, which the IAU named for provinces of the ancient Roman Empire: Baetica, Achaia, Etruria, Narbonensis, Noricum, Pannonia and Raetia. The unobserved region of the southern hemisphere was named after Hermann Goldschmidt, who discovered the asteroid in 1852.

The Baetica region is situated around the north pole, and includes a cluster of superimposed craters named the North Polar Crater Cluster (three of which exceed 10 km across), as well as their impact deposits. This is the youngest surface unit on the asteroid.

Baetica is covered by a smooth ejecta blanket approximately 600 meters thick that partially buried older craters. Other features include landslides, gravitational rock slides, and blocks of ejecta up to 300 meters in size. The landslides and corresponding rock outcrops are generally brighter than their surroundings.

The two oldest regions – Achaia and Noricum – are both heavily cratered. The Narbonensis region coincides with the largest impact crater on Lutetia, 56 km wide Massilia, which was modified by pit chains and grooves at a later date. Pannonia and Raetia are probably impact craters. Noricum is transected by a prominent groove 10 km long and about 100 meters deep.

Numerical simulations have shown that the impact that produced the largest crater on Lutetia seriously fractured, but did not shatter, the asteroid. So Lutetia has likely survived intact from the beginning of the Solar System. The presence of linear fractures and the morphology of the impact craters also indicate the interior has considerable strength and therefore is not a rubble pile like many smaller asteroids.

Studies of the fracture patterns indicate that an impact crater up to 45 km across may exist in the unseen southern hemisphere (see Fig. 7.33). This was given the nickname Suspicio crater. Lineaments imply a location for this crater in the southern hemisphere consistent with that of hydrated minerals detected by ground-based telescopes.

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[2] Generally, an ancient surface displays many more impact craters than a younger surface, because more time has passed for the object to experience bombardment by meteoroids and comets. There are models for the size distribution of potential impactors over time.

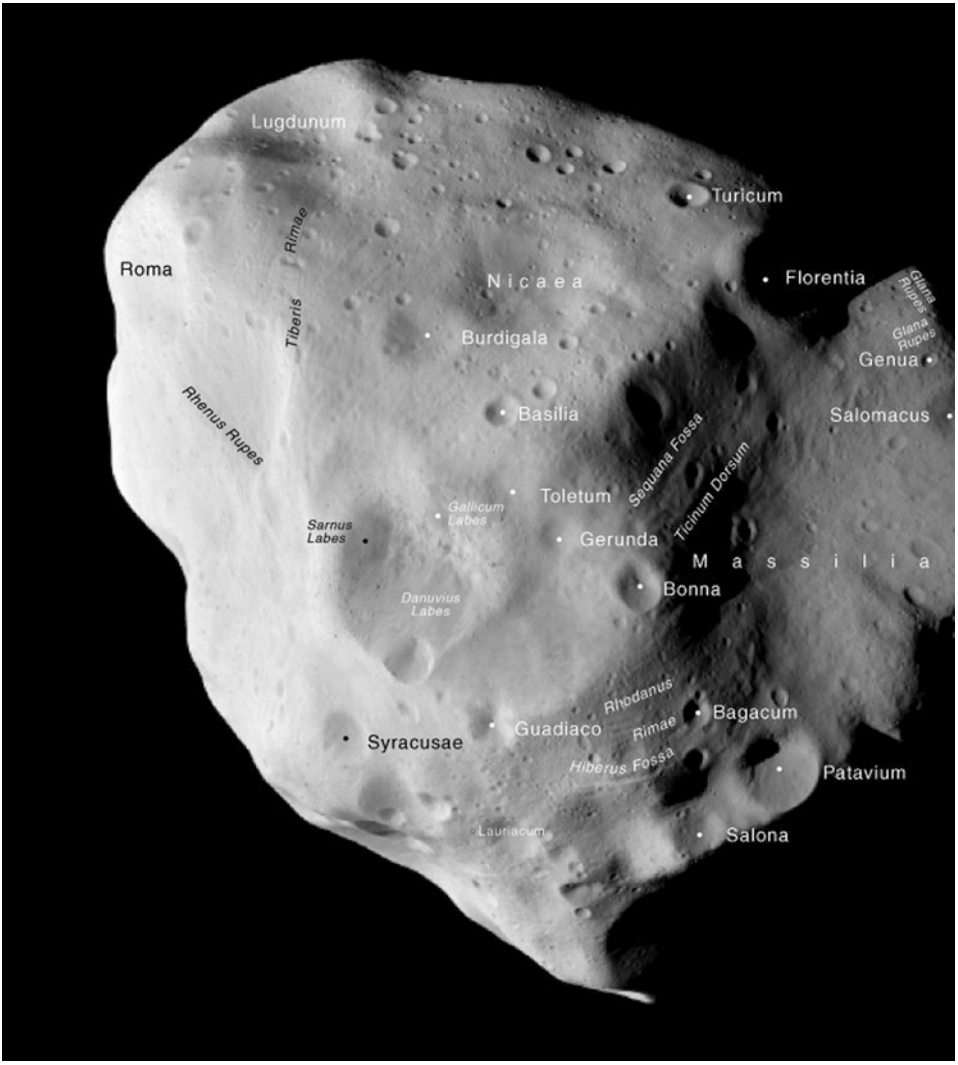

Fig. 7.31: Named features on Lutetia. The most notable impact craters were named after cities which existed around the same time as the city of Lutetia (the Roman name for Paris, France). The largest, 56 km in diameter, is Massilia, the Roman name for Marseille. Other features were named after rivers of the Roman Empire and adjacent parts of ancient Europe. (ESA 2010 MPS for OSIRIS Team MPS/UPD/LAM/IAA/RSSD/INTA/UPM/DASP/IDA)

Apart from 19 craters named after cities in the ancient Roman Empire, with the largest, Massilia, named after the ancient city now known as Marseille, most of the other features on Lutetia were named after rivers in Europe around the Roman era.

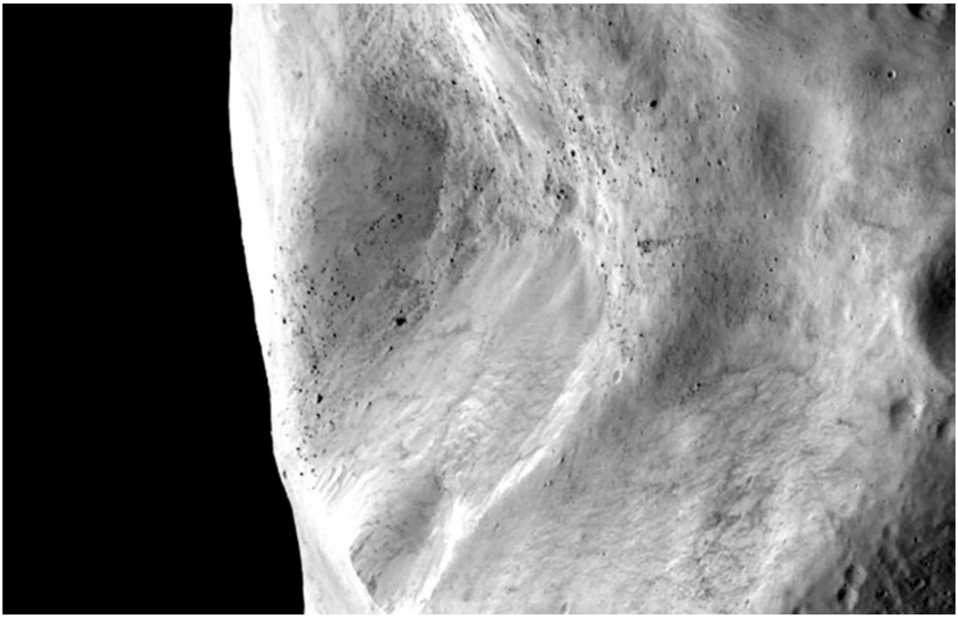

Fig. 7.32: This close-up view of a crater in the Baetica region shows boulders and landslides. Several hundred dark boulders up to 400 meters across are scattered around the crater's sides. These are some of the largest rocks found thus far on small bodies in the Solar System. The landslides probably occurred when impacts elsewhere on the asteroid caused vibrations that dislodged loose regolith. (ESA 2010 MPS for OSIRIS Team MPS/UPD/LAM/IAA/RSSD/INTA/UPM/DASP/IDA)

Some parts of Lutetia are covered in a thick layer of regolith, or unconsolidated material that comprises loosely aggregated dust particles around 50-100 micrometers in size. Over billions of years the surface has probably been pulverized by impacts. Much of the ejecta would have escaped to space, but a lot of it would have fallen back, producing a layer of loose material up to 600 meters thick. In the low gravity, the vibrations from nearby impacts have created giant landslides.

OSIRIS also imaged numerous dark boulders strewn across the surface (see Fig. 7.32), some of them 300-400 meters across, or about half the size of Ayers Rock (Uluru) in Australia.

The VIRTIS spectrometer recorded a maximum surface temperature of –19°C on the sunward hemisphere and a minimum of –103°C on the night hemisphere (see Fig. 7.35). There was no evidence of ancient chemical processes involving water, or space weathering.[3]

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[3] Angioletta Coradini, the VIRTIS principal investigator, passed away shortly after Rosetta's fly-by, during the preparation of a key paper for the journal Science that was eventually published on 28 October 2011.

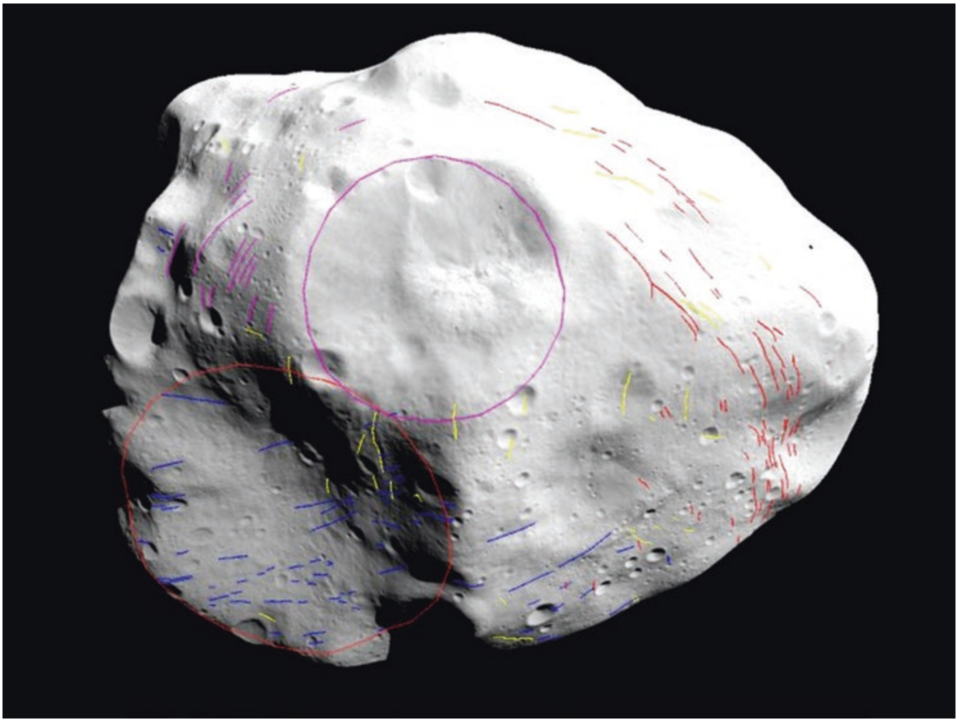

Fig. 7.33: An OSIRIS image of Lutetia centered on the North Pole Crater Cluster (the purple outline), with Massilia crater at the lower left (red outline). Red and purple lines indicate the concentric grooves or 'lineaments' associated with these craters. Those colored blue suggest there is a large crater (nicknamed Suspicio) on the unseen hemisphere. Yellow denotes other linear features. (ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/ UPM/DASP/IDA)

So what is Lutetia made of? VIRTIS obtained hyperspectral images with a spatial resolution varying from 12 km to less than 1 km at closest approach. These indicated the composition of the surface to be remarkably uniform and mainly primordial chondritic (silicate) material, but this could merely represent a bland surface veneer.

Additional observations by OSIRIS, MIRO and ALICE aboard Rosetta, visible studies by the New Technology Telescope of the European Southern Observatory, Chile, and near-infrared and mid-infrared data from NASA's Infrared Telescope Facility in Hawaii and by the Spitzer Space Telescope were combined to study Lutetia across a very wide range of wavelengths in order to deduce its surface composition. This was the most complete spectrum of an asteroid ever assembled. It was compared against spectra of meteorites found on Earth that have been extensively analyzed in laboratories. Only the enstatite chondrite type of meteorite

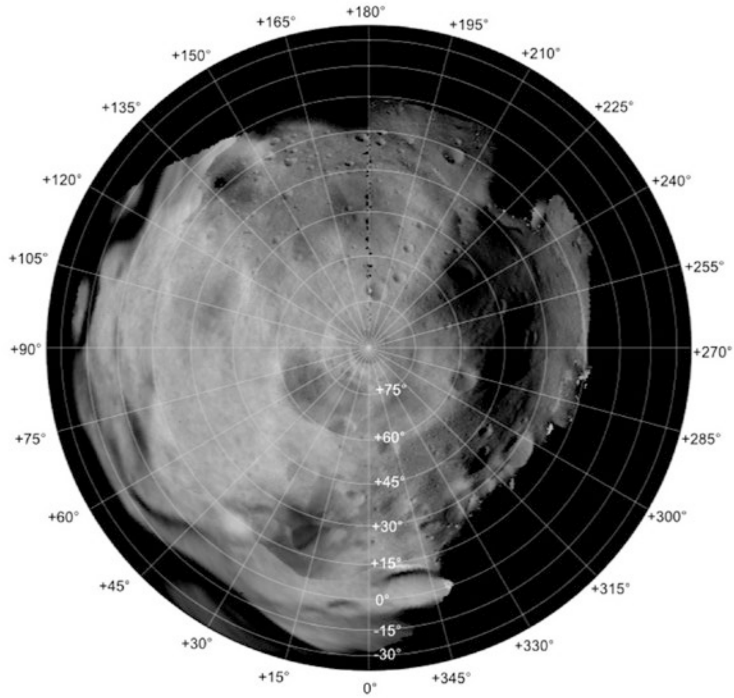

Fig. 7.34: A map of Lutetia centered on its north pole showing the area viewed by Rosetta. It covers most of the northern hemisphere and part of the southern hemisphere. The number of craters in different regions indicates the age of the surface, ranging from 3.6 billion years old to a relatively youthful 50-80 million years old. (ESA 2011 MPS for OSIRIS Team MPS/UPD/LAM/IAA/RSSD/INTA/UPM/DASP/IDA)

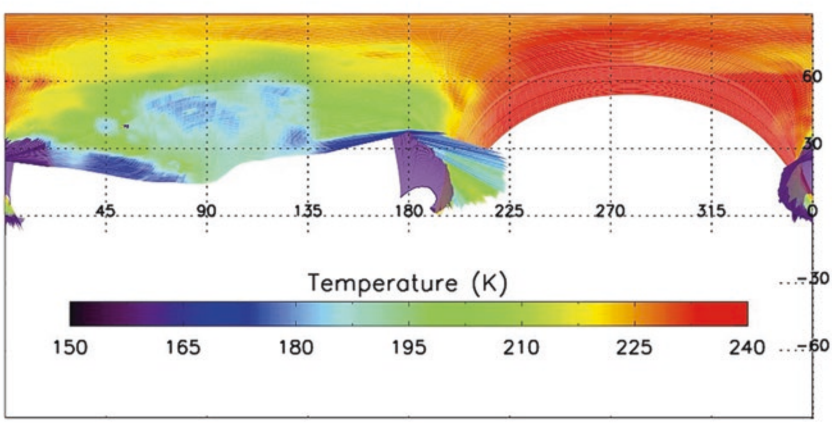

Fig. 7.35: A false-color temperature map of Lutetia obtained by the VIRTIS instrument. The highest temperature (red) was on the daylight hemisphere, where the Sun was overhead. The minimum temperature measured (purple) was on the night side. Notice the low temperatures in some of the smaller craters (left). (LESIA)

proved to have properties that matched Lutetia's over the full range of colors,[4] but other characteristics suggested a surface composition compatible with primitive, carbon-rich meteorites known as carbonaceous chondrites.

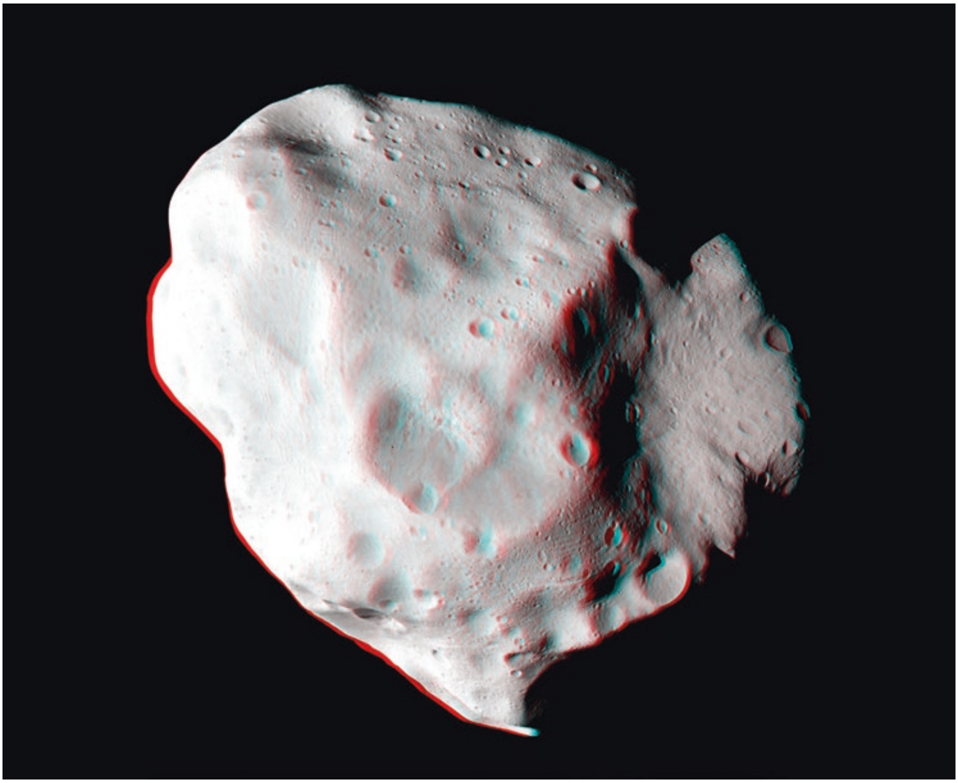

Fig. 7.36: This 3D image of Lutetia can be viewed using stereoscopic glasses with red-green or red-blue filters. It was created by combining two separate images obtained several minutes prior to Rosetta's closest approach to the asteroid. (ESA/H. Sierks MPS)

Based on images taken by OSIRIS, Rosetta scientists modeled the asteroid's shape. They also studied deflections in the spacecraft's trajectory caused by the weak gravity, inferred from the radio signals received at Earth. This indicated a mass of 1.7 million billion tonnes.

"The mass was lower than expected. Ground-based observations had suggested much higher values," reported Martin Pätzold from the University of Cologne, Germany, the leader of the radio science team.

[4] Enstatite chondrites (a.k.a. E chondrites) account for only about 2% of recovered meteorite falls. The fact that they are the only chondrites to have the same isotopic composition as Earth and the Moon strongly implies that enstatite chondrite formed at about 1 AU from the Sun, and that our planet was formed by the accretion of this material.

Having a mass and a volume, it was possible to calculate the bulk density. At 3.4 g/cc, which is comparable to our Moon, Lutetia proved to have one of the highest asteroid densities thus far measured. This would be fairly easy to explain if Lutetia were completely solid, free of voids or cracks, but researchers studying the impact craters found huge fractures throughout, suggesting it is fairly porous. This would lower its bulk density considerably. To explain the combination of a high density and a porous interior, it has been argued that the asteroid must contain significant quantities of iron.

Like the rocky terrestrial planets, many of the larger asteroids, such as Lutetia, are thought to have grown large enough to differentiate internally, melting with heat released by radioactive isotopes in the rocks. The denser elements, such as iron, would then sink to the center and the lighter rocky material would float to the top.

In the case of Lutetia, it would seem that it was subjected to some internal heating early in its history, but did not melt completely and so did not end up with a well-defined iron core.

If this is the case, Lutetia, as the first asteroid known to be partially differentiated, provides a rare snapshot of the early development of planetary bodies. Perhaps it achieved sufficient size to develop a core that was at least partially molten, whilst avoiding the larger collisions which accelerated planet formation.

This implies that Lutetia is more like a planetesimal, or a planet precursor, than a fragment of a larger parent asteroid or a rubble pile that broke apart, as most known asteroids seem to be. Most of the bodies of the inner Solar System disappeared after several million years, as they were incorporated into the newly accreting planets. Some of the largest, such as Lutetia, were ejected to safer orbits farther from the Sun.

What caused this ejection? One possibility is that its orbit was dramatically altered by a close encounter with one of the rocky planets. An encounter with the young Jupiter during the giant planet's migration to its current orbit could also explain the change in orbit that left Lutetia in what became the main asteroid belt.[5]

Lutetia's birthplace in the inner Solar System, and subsequent relocation, would explain why its color and surface properties differ so much from most of the asteroid population. Similar asteroids represent less than 1% of the population of the main belt. The new findings explain why Lutetia is different: it is a very rare survivor of the material from which the rocky planets were formed.

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[5] Many astronomers believe that Jupiter orbited closer to the Sun in the early Solar System, before migrating out to its current position. Its huge gravitational attraction would have disrupted the orbits of the other objects in the inner Solar System at that time.

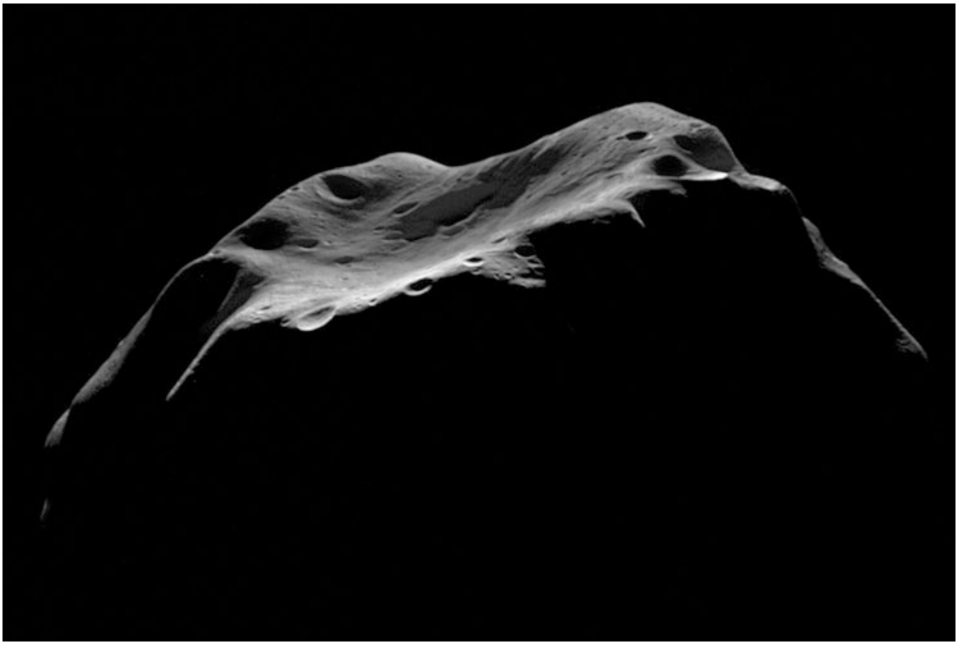

Fig. 7.37: An OSIRIS view of Lutetia as Rosetta left the asteroid behind. (ESA/MPS/UPD/LAM/IAA/RSSD/INTA/UPM/DASP/IDA/Daniel Machacek)

7.14 DEEP SPACE HIBERNATION

Payload operations associated with the Lutetia fly-by were completed on 11 July, with all of the instruments apart from SREM shut down. The next three weeks were mainly dedicated to downlinking the large volume of science data acquired.

On 12 July, when Rosetta was more than 406 million km from the Sun, it captured the record for the farthest distance from the Sun to be flown by a solar-powered spacecraft, surpassing the distance record previously held by NASA's Stardust comet mission. As it pushed on, the energy in sunlight became weaker and the temperatures continued to fall. On 22 July, Rosetta exceeded its own previous maximum distance from Earth. During August, Rosetta remained in active cruise mode. On 20 August, there were tests of the high-gain antenna and low-gain antennas. These verified that it was possible to command the spacecraft from the New Norcia and DSS-43 ground stations across 3 AU using the low-gain antenna at a data rate of 7.8 bps. Both stations also detected a regular variation in the signal from the high-gain antenna that was achieved by commanding the spacecraft's dish to simulate a strobing signal by sweeping its beam across Earth several times.

On 3 September, the performance of the solar arrays was tested by tilting them relative to the Sun direction in order to simulate deep space conditions.

Meanwhile, there was concern about the condition of the spacecraft's four reaction wheels. High friction in wheel B had been noted after the Steins fly-by, with the likelihood it would cease to operate within several months. A similar problem arose with another reaction wheel the following year.

Rosetta began using three reaction wheels for attitude control on 15 July 2010, when wheel B was switched off because of two failed relubrications.[6] There were no plans to restart it until after the end of the long period of deep space hibernation. Then, on 27 August, wheel C started to exhibit a very noisy frictional torque. With its behavior degrading, the ground team decided to undertake a relubrication, and to operate wheel C at lower speeds (less than 1,000 rpm) except for slew maneuvers. It was also decided not to use the reaction wheels in safe mode from 13 November onwards. Fortunately, on 24 November, a second relubrication resulted in some improvement in wheel C's performance.

However, the condition of the wheels continued to cause considerable concern. In case the spacecraft woke up after hibernation with only two operational wheels, the operations team developed a new attitude and orbit control system (AOCS) mode with industry, based on the use of two active wheels and the thrusters. This software was fully ready and tested for uplink in case it was ever needed, but it was never used.

"Meanwhile we fully changed how we operated the wheels," explained Sylvain Lodiot. "The user manuals told us we had to operate them at high speed, but the evidence indicated the opposite. So we embarked on a year-long test with a real spare wheel on a full scale model of Rosetta at ESOC. This also involved sending the wheel back to the manufacturer for opening and bearing checking. After all the tests, the wheel was still fine, so at wake up, we changed all the settings on board to allow operating around zero speed, and that worked!"

Another unwelcome complication arose on 9 September, when a test procedure to switch to the redundant reaction control system (RCS) pressure regulator was completed. This revealed that there was a leak of pressurant in a section of piping which was common between the two regulators.

The first indication of such a problem had arisen in September 2006, when a pressure reading in the RCS had dropped unexpectedly to zero at a time when Rosetta was not in contact with Earth. The reason for this sudden drop in pressure was uncertain, but a leak was regarded as a possibility.

Once the leak was confirmed, the faulty section of piping was isolated, forcing the mission team to modify planned operations and to cancel the planned repressurization of the RCS in January 2011. The system would have to be operated using the existing pressure, in so-called 'blow-down' mode.

An investigation was then launched to determine the implications of the new procedures. Ground tests on one thruster were undertaken in an effort to characterize the behavior of Rosetta's 24 thrusters at low pressure, whilst other work

[6] Each wheel had its own internal oil reservoir.

ensured optimal thermal control of the propellant tanks in future rendezvous maneuvers. Although the new procedure increased operational uncertainties, the mission team eventually decided they still had plenty of safety margin.

The development of a new rendezvous maneuver strategy was greatly assisted by the fact that fuel allocated for dealing with uncertainties on maneuvers in the early part of the mission was still available. The new strategy meant delaying the start of the post-hibernation rendezvous maneuver at Comet 67P by about a week, but this was within the uncertainties involved in the overall timeline for comet operations. The rest of the mission maneuvers would be performed with the propulsion system at low pressure, delivering lower (but still acceptable) efficiency. There should be no impact on the comet science operations, and the date for lander delivery would remain within the planned window.

During 2-31 October, Rosetta was in superior conjunction, while passing behind the Sun as viewed from Earth. It operated in active cruise mode, but with severely limited ground station communication because of the influence of the Sun on the radio transmission. NASA's Deep Space Network provided additional support to the radio science investigations. Downloading of the mass memory was not attempted between 10-23 October, when the telemetry link was particularly poor.

Meanwhile, preparations continued for the forthcoming entry into Deep Space Hibernation Mode (DSHM), the prolonged period when the spacecraft would be largely shut off in order to conserve power and propellant.

On 19 November, the team carried out a similar test to the one on 20 August, to ensure that the ESA and NASA ground stations would be able to command Rosetta when using its low-gain antenna and detect the strobing signal from the high-gain antenna as the spacecraft was spinning. Undertaken with continuous low-gain antenna coverage, this test validated the radio communication activities and performance to be expected after entering DSHM in July 2011, when Rosetta would be at about 4.4 AU from Earth.

The final payload checkout prior to hibernation (PC13) was successfully carried out in early December, with no major problems arising.

The first key task in January 2011 was a large trajectory correction, known as the first rendezvous maneuver. This was intended to include five burns of the propulsion system, with an optional extra firing in the event that a final tweak was needed.

The first burn (RDVM 1A) proceeded as planned on 17 January, with the 393 minute event altering Rosetta's velocity by 300 m/s.

On 18 January, during the second planned burn, there was a large performance anomaly in the reaction control system (RCS), evidently caused by an issue with thruster 9A. This led to an attitude pointing error that prompted the spacecraft to enter a level two safe mode. RDVM 1B was to have delivered a delta-V of 274 m/s, but it was terminated after only about 30 m/s.

After recovering the spacecraft, the mission control team at ESOC revised the RCS operating mode to preclude a repeat of the problem. In addition, the replanned maneuver sequence was to be performed using the redundant set of thrusters.

The new sequence comprised the RDVM1 Test Burn (35 m/s) on 21 January, followed over the next three days by RDVM 2A (160 m/s), RDVM 2B (200 m/s) and RDVM 2C (45 m/s). Overall, this achieved 98% of the required trajectory change. The residual (17.3 m/s) was left to a final trim maneuver scheduled for 10 February.

Unfortunately, this maneuver was aborted after several seconds because Rosetta entered safe mode in response to an attitude pointing error that exceeded the failure detection isolation and recovery (FDIR) system's limit of four degrees for the first 100 seconds of the maneuver. The pointing error was due to an operational oversight, in which a command that was to adjust the spacecraft's attitude prior to the burn was not uplinked.

The good news was that, during the few seconds that the burn lasted, RCS branch A had operated as expected, using the commands issued by the attitude and orbit control system. The safe mode was promptly recovered and the spacecraft was prepared once again to carry out the trim maneuver.

The spacecraft trim maneuver, rescheduled for 17 February, successfully provided a delta-V of 17.29 m/s. The burn, which lasted about 29 minutes, was completed about 30 seconds earlier than predicted, indicating a slight over-performance of the thrusters relative to expectations.

Despite the off-nominal performance of the RCS during the trim maneuver and while making the short, sporadic pulses to offload the reaction wheel, the performance of RCS-A confirmed that no permanent failure was present in this branch. The 'problem' appeared to lie with the modeled predictions the engineers were using for cold-starting the thrusters at low pressures.

Precise orbit determination following the RDVM 1 burns showed this maneuver was almost perfect, so plans for a possible further correction were shelved. The outcome was that Rosetta was now on a fly-by trajectory for Comet 67/P with a perfectly acceptable 'miss distance' of about 50,000 km.

After the completion of the RDVM 1 activities, the spacecraft was changed back to its normal configuration on 4 March, before completing pre-hibernation activities. One key activity was a check of the performance of the solar arrays at 4 AU (600 million km from the Sun), giving satisfactory results.

During March, Rosetta continued in active cruise mode, with most scientific instruments off. The main activities were the preparation of the instruments for deep space hibernation, using OSIRIS and the NAVCAMs to image Comet 67P and the area of sky that would be observed during the approach to the comet, as well as characterizing the spacecraft's inertia properties and the Sun acquisition sensors.

During the long range imaging on 26 March, an anomalous acceleration of the spacecraft was observed. The most likely explanation was thought to be outgassing of products accumulated during the rendezvous maneuver in January.

On 15 May, Rosetta was 654 million km (4.37 AU) from the Sun. It was also 508 million km (3.39 AU) from Earth, so the one-way signal travel time was 28 minutes 15 seconds.

Deep Space Hibernation Begins

Starting in mid-May, the mission team concentrated on their final preparations for the Deep Space Hibernation Mode. A final performance test of the solar arrays was conducted, and all the commands for entering into hibernation were uploaded in a disabled state. By early June, the spacecraft was configured in readiness for the onset of the hibernation.

Rosetta was successfully spun-up and commanded into DSHM on 8 June. The maneuver was executed without any problems. The spacecraft's signal was lost on the ground at about 08:00:35 UT when the spin-up maneuver was triggered on board. (The slow spin would impart stability while the spacecraft was asleep.)

The 70 meter diameter antenna of NASA's DSS-43 in Canberra detected an extremely weak strobing signal. This confirmed that the spacecraft had successfully executed the most critical phase of the maneuver. About 50 minutes later, after estimating the real spin axis, Rosetta's onboard software refined the high-gain antenna direction. The strength of the received signal increased sharply to the same level as when the spacecraft was not spinning.

Once the ground checks of the strobing period and signal strength were completed, the telecommand link was verified by switching the spacecraft's telemetry modulation on and off twice and monitoring the change in signal strength. The final telecommand to authorize entry into hibernation was released at 12:57:40 UT. Confirmation of success came at 14:12:00 UT, when the final pulse from the spacecraft was received by the ground stations.

To ensure that all had proceeded as planned, a passive monitoring phase of six days was then undertaken.

Rosetta now began the coldest, most distant leg of its journey as it raced away from the Sun, out toward the orbit of Jupiter. It was oriented so that its solar panels faced the Sun to collect as much of the diminishing sunlight as possible.

For the next two and a half years, the spacecraft was on its own, leaving the mission team to look forward in eager expectation to the long-awaited rendezvous with Comet 67P.

During its hibernation, Rosetta would achieve the following record distances: 792 million km (5.29 AU) from the Sun on 3 October 2012, then 937 million km (6.26 AU) from Earth on 1 December 2012.

Rosetta's awakening was set for 10:00 UT on 20 January 2014, at which time it would be 672 million km (4.49 AU) from the Sun and 807 million km (5.39 AU) from Earth.

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